

# CFD Analysis in Advance of the NASA Juncture Flow Experiment



June 8, 2017

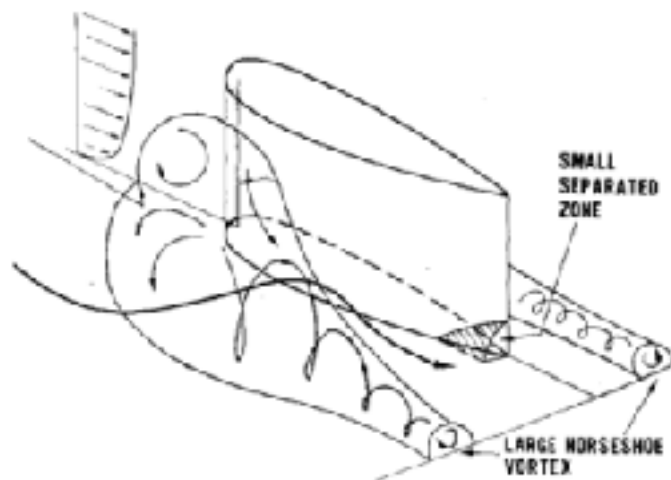
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# Juncture Flow

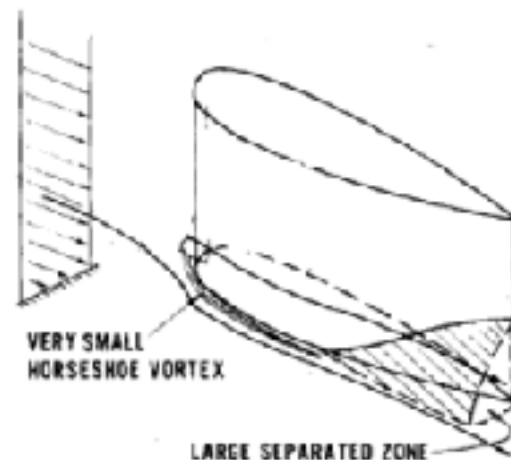
Sponsored by NASA's Transformative Aeronautics Concepts Program's Transformational Tools and Technologies (T<sup>3</sup>) project

- Substantial effort to investigate the origin of separation bubbles found in wing-body juncture zones
- Primary goal is to gather validation level data, for future CFD code & turbulence model development
- Multi-year effort including several large-scale wind tunnel tests
- Computational Fluid Dynamics (CFD) used in both design and support of risk reduction experiment



(a) thick boundary layer

Model proposed  
by Barber *et al.*

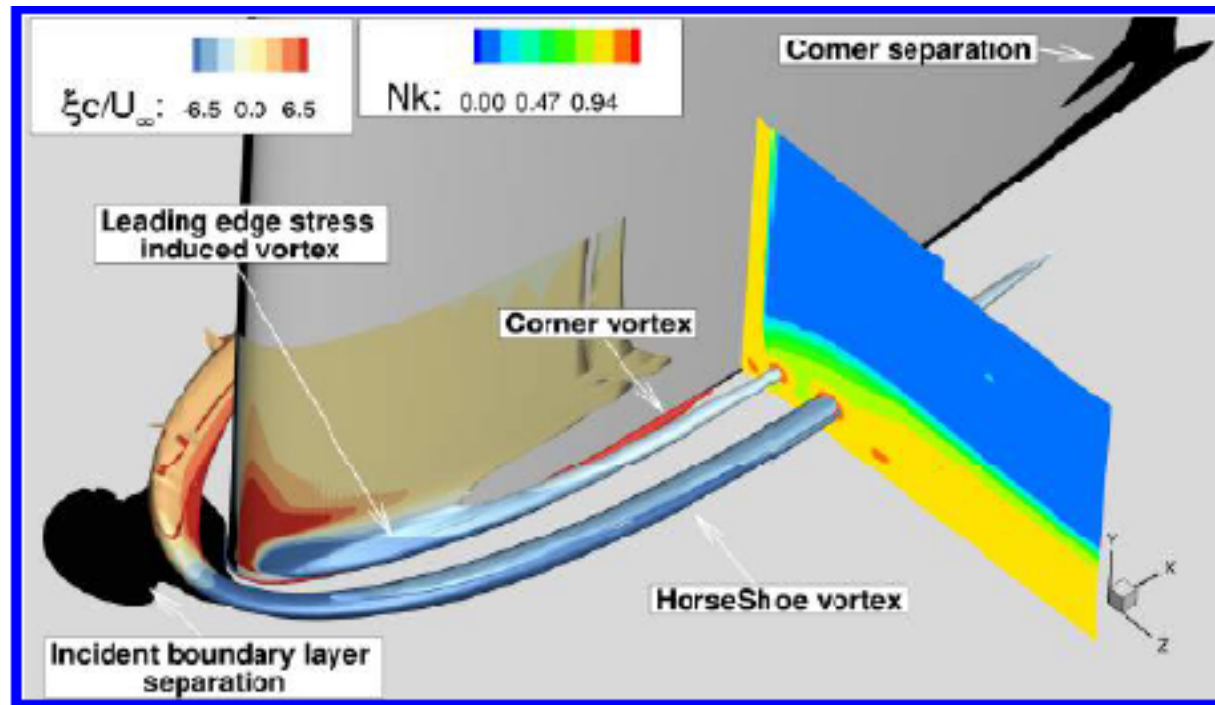


(b) thin boundary layer

# Background

- Flow physics of juncture flows is complex
  - Several vortical structures coexist: e.g., Horseshoe Vortex (HSV), corner vortex, stress-induced vortex
  - Many factors—such as incoming boundary layer momentum thickness, wing bluntness, and wing sweep—also play some role

- Previous juncture flow work:
  - Simpson et al
  - Gand et al
  - other references mentioned therein



From AIAA-2014-2690 (Bordji et al)

# Background



- Geometric junctures (corners) are common on aircraft
  - CFD predictive capability is currently uncertain
  - E.g. Drag Prediction Workshops, participants predicted a wide range of wing-body corner separation bubble sizes (none to very large)
- Computed juncture bubble may be influenced by: grid size, grid topology, and numerical treatments
  - Accurate modeling of the Reynolds stresses is needed
  - Non-linear turbulence modeling
- Because of the high degree of uncertainty in the CFD predictions, relevant separated corner flow experiments focused specifically on obtaining high-quality data for CFD validation are needed

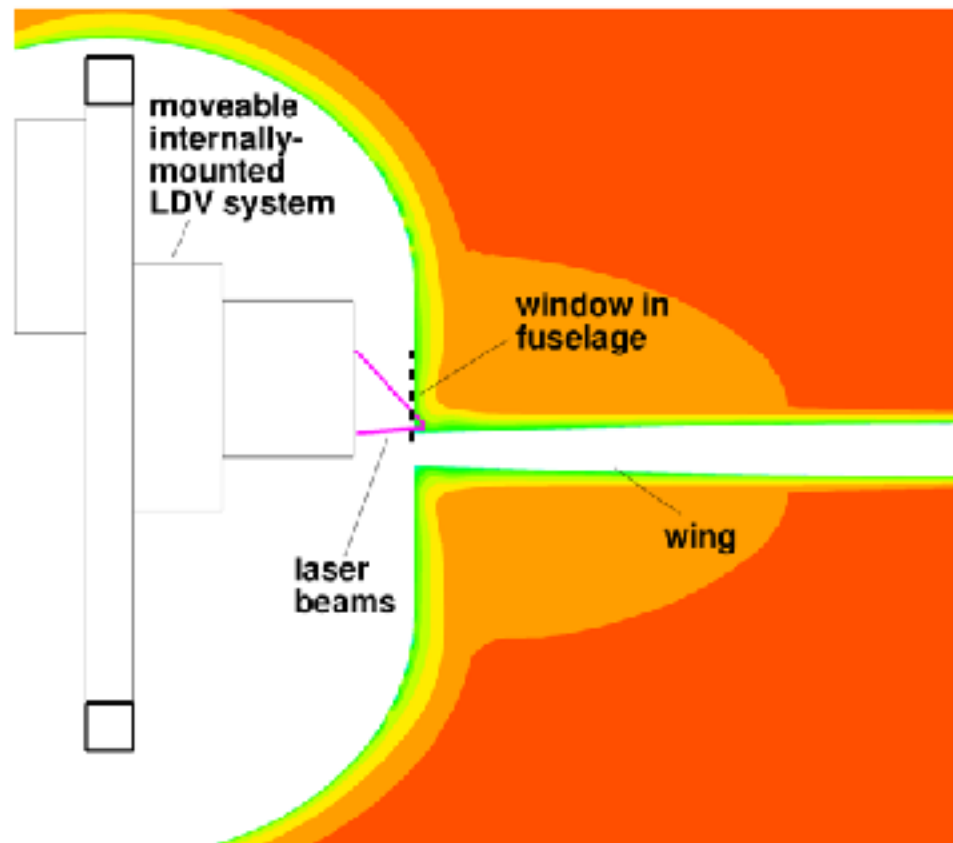


# Past Experiments

- Simpson et al experiments:
  - Mostly focused on HSV (not so much on corner separation)
- Gand et al experiments:
  - NACA 0012 wing (no sweep) mounted on flat plate - did not separate
  - Twisted NACA 0015 wing (no sweep) mounted on flat plate - produced corner separation at  $\alpha=12$  deg
- New NASA experiment originally conceived by members of the DPW steering committee
  - Swept wing / fuselage full-span configuration
  - To focus primarily on collecting data for CFD validation
  - A main objective: to obtain flow field details very near the corner

# Goals and Purpose

- Decision made early: to use internal Laser Doppler Velocimetry (LDV) system
  - Mounted inside of the fuselage on a movable three-axis traverse system
  - Will measure the flow field very near the wing-body juncture through window(s) in the fuselage

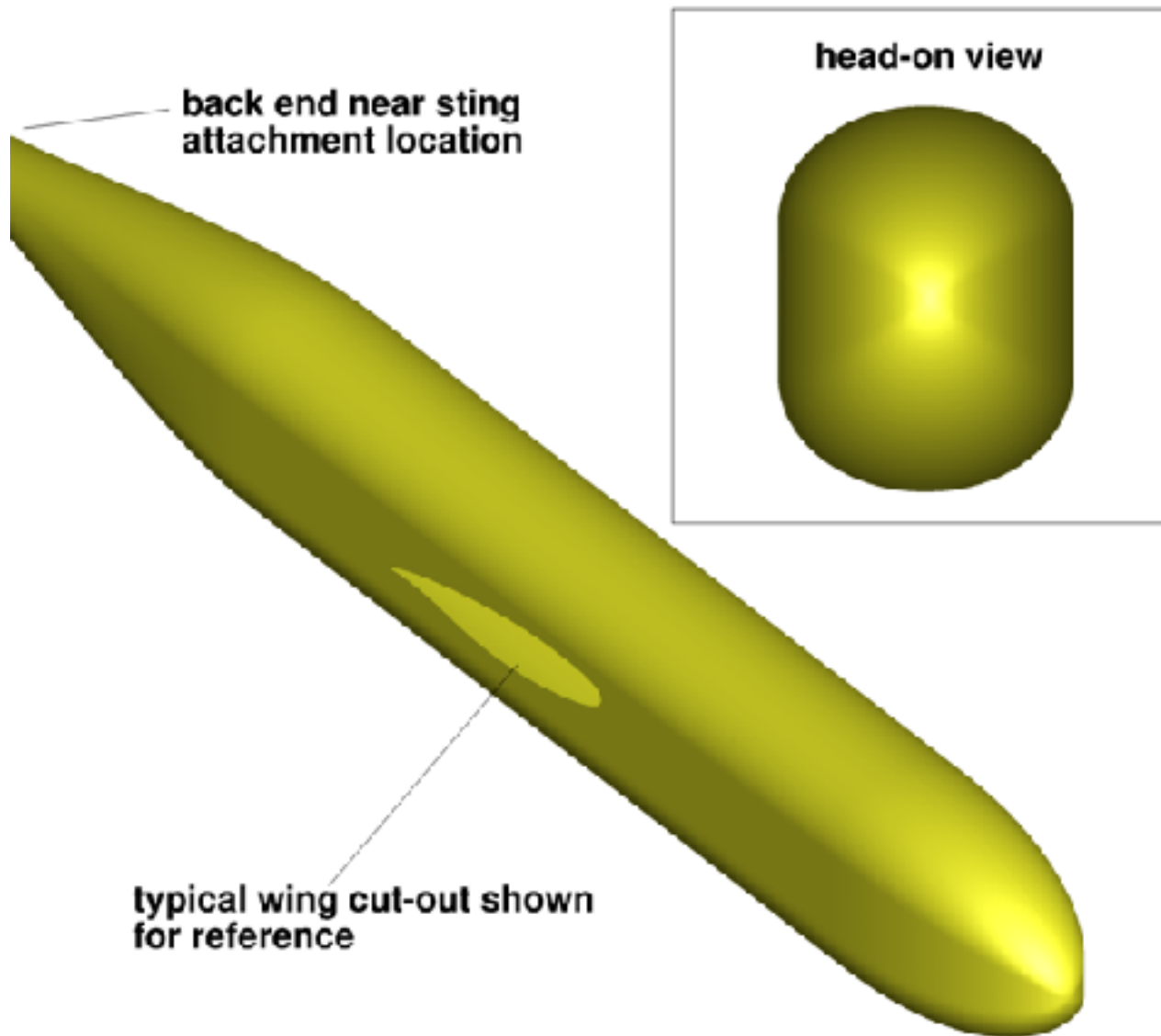


# Goals and Purpose



- Decision made to perform a subsonic experiment
  - Subsonic testing venues of sufficient size were readily available
  - $M=0.2$
  - 8% model based on full scale CRM (~16 ft long, 11 ft wide)
- “CFD Validation-Quality”
  - Boundary conditions, geometry information, experimental uncertainties, etc., necessary for a thorough and unambiguous CFD validation study
  - See, e.g., Aeschliman & Oberkampf (AIAA J 36(5):733-741, 1998)
- Main purpose:
  - Assess the ability of existing models to predict the onset and extent of the three-dimensionally separated flow near the Wing Junction Trailing Edge region of a full-span wing-body configuration, in terms of the surface topology of the flowfield structure.
  - To provide a range of prediction difficulty, a variation of low fields are required, including the onset and progression of corner separation

# Fuselage Configuration

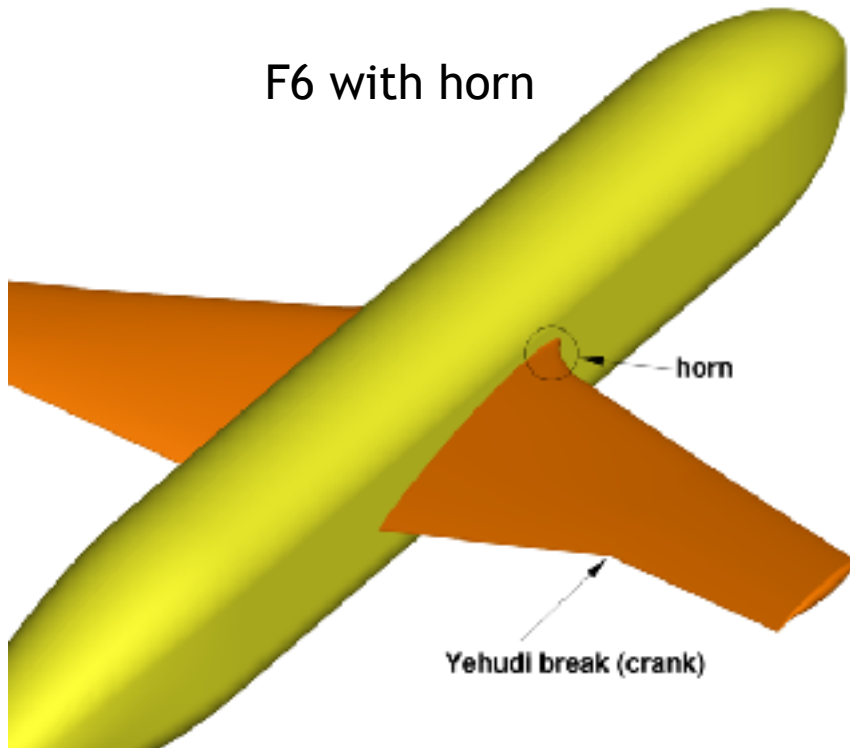


# Wing Configuration

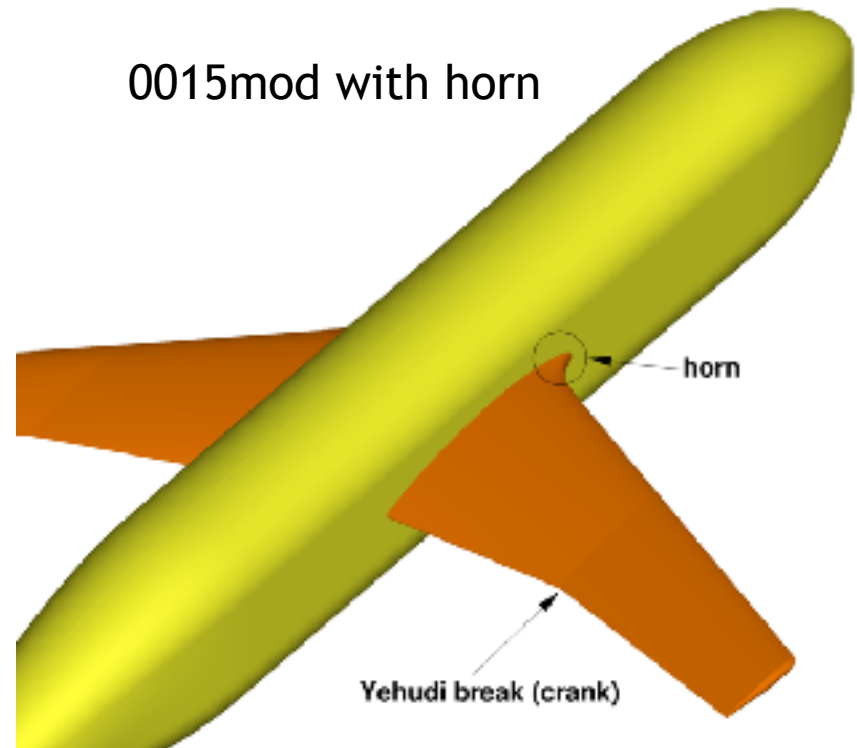


- Planforms based on truncated DLR-F6 or truncated CRM

F6 with horn



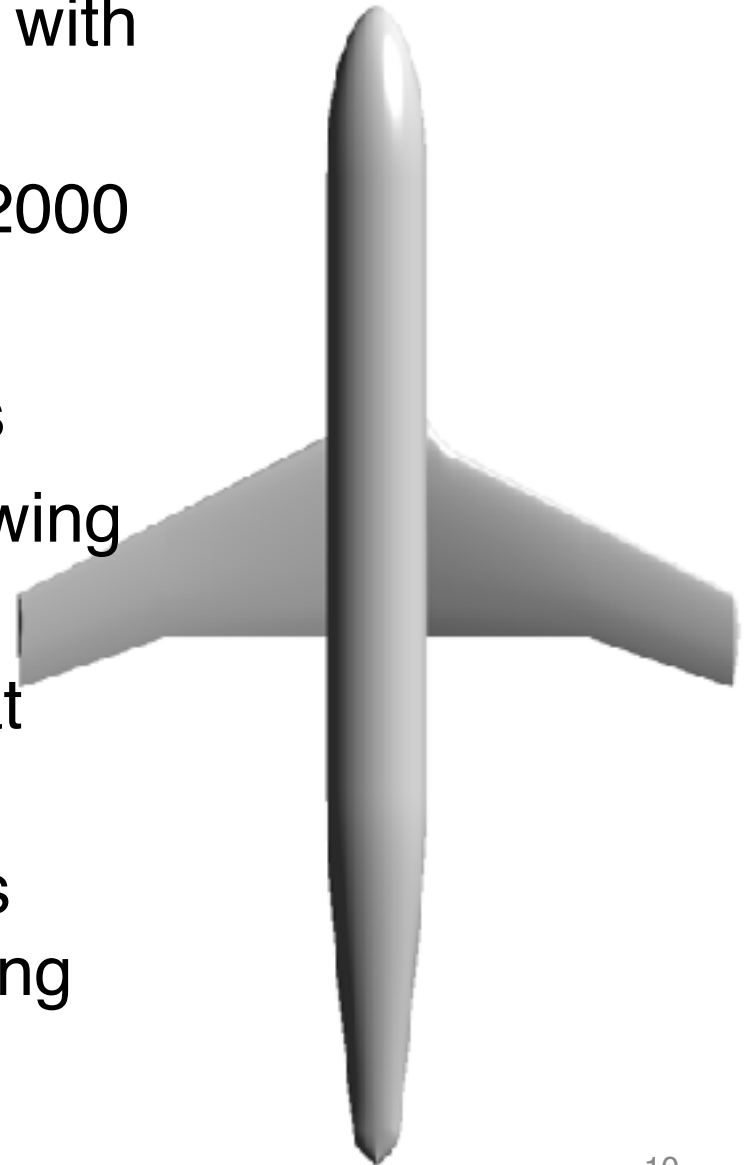
0015mod with horn



# Juncture Flow Model Design



- Preliminary model design done with CFD
  - Overflow 2.2L: SARC-QCR2000
  - FUN3D: SARC-QCR2000
- Evaluated 20+ wing candidates
- Committee down-selected the wing candidates
- Selected 6 wing candidates that combined satisfied the goals
- Risk reduction experiment tests proposed: further evaluate 6 wing candidates

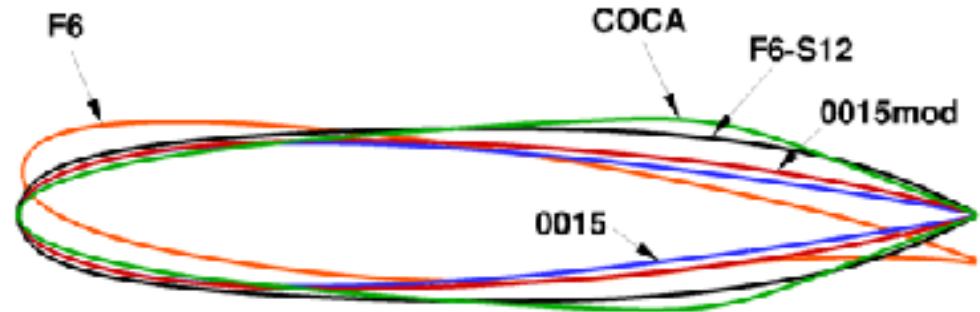


# Wing Candidates

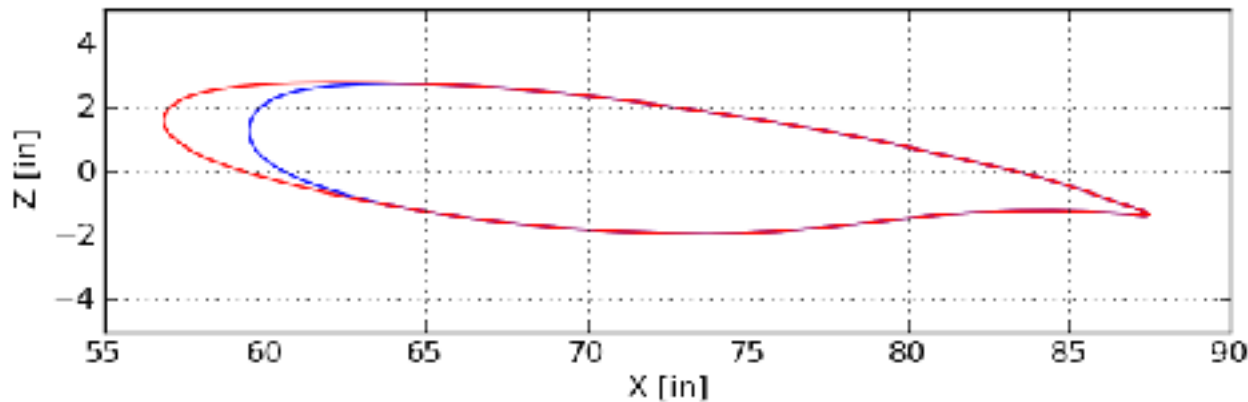


## 6 Wing candidates

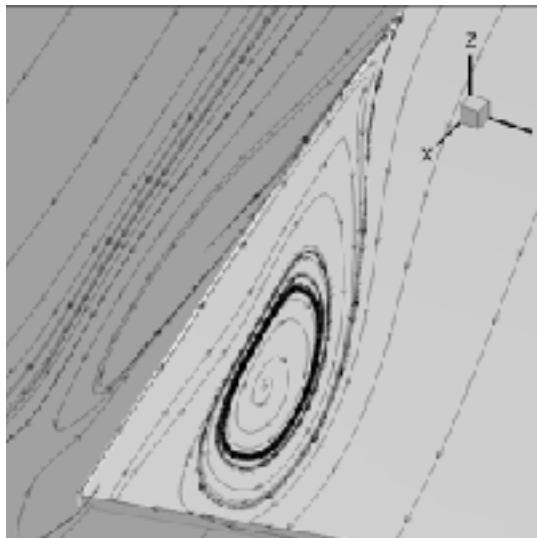
- DLR-F6 no horn
  - Used in DPW3
  - Showed side of body separation
- DLR-F6: with LE horn
- NACA 0015 with horn: symmetric wing
- NACA 0015mod: slightly steeper pressure recovery
- F6S12: symmetric F6 variant
- COCA
  - Coder-Campbell design
  - CDISC/skin-friction constraints



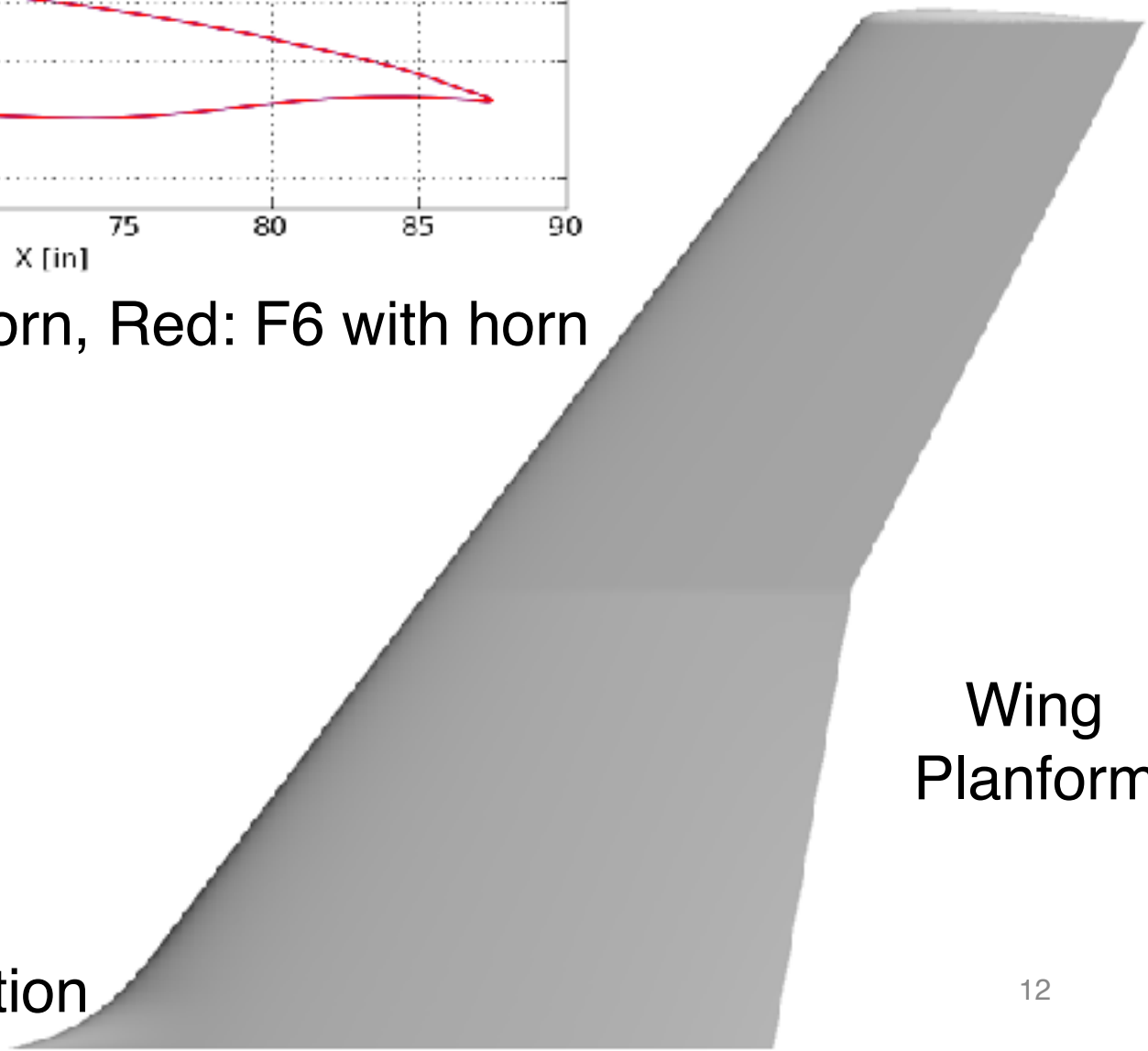
# DLR-F6



Blue: F6 without horn, Red: F6 with horn

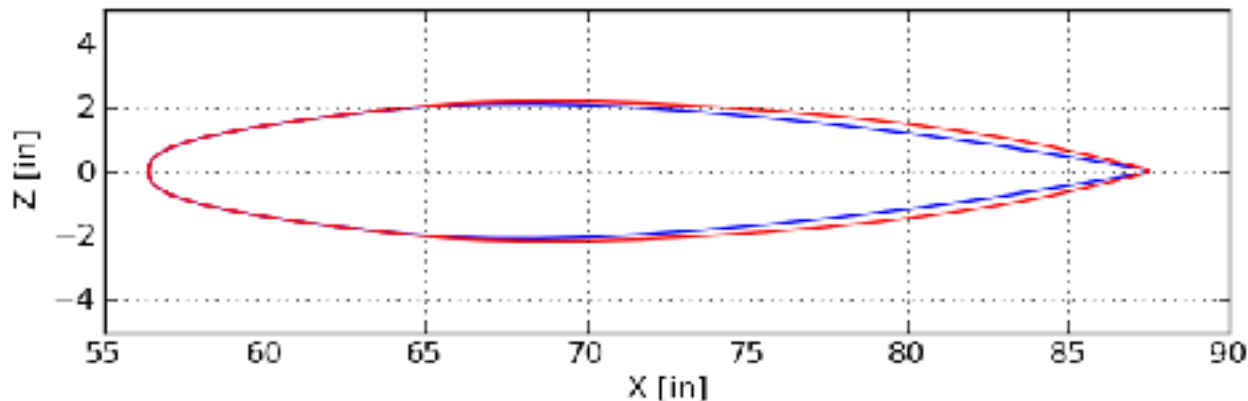


Side of Body Separation

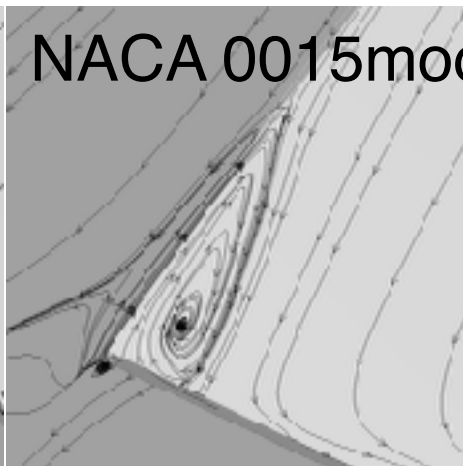
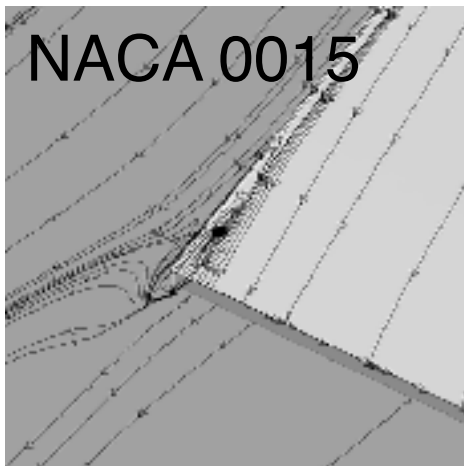


Wing  
Planform

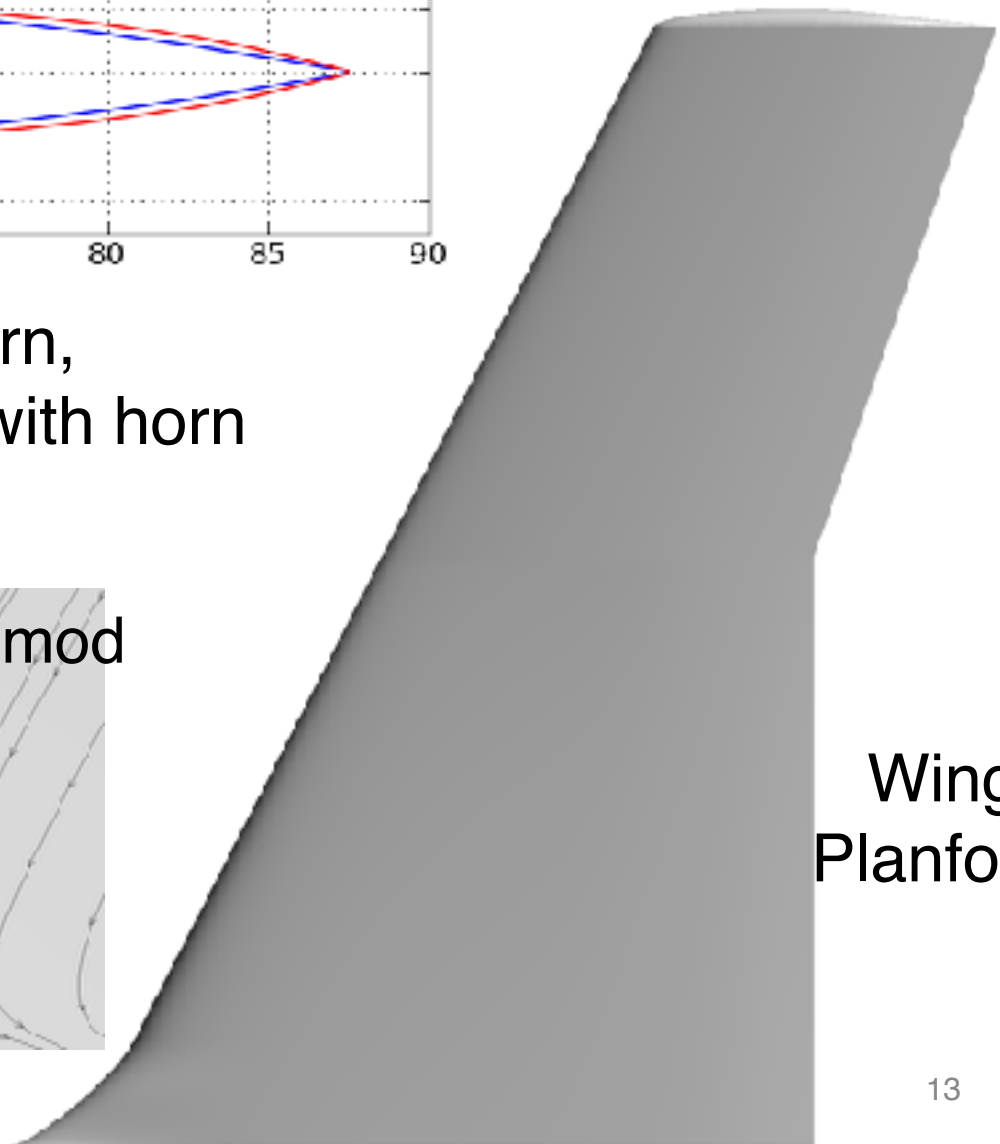
# NACA 0015 — NACA 0015mod



Blue: NACA 0015 w/horn,  
Red: NACA 0015mod with horn

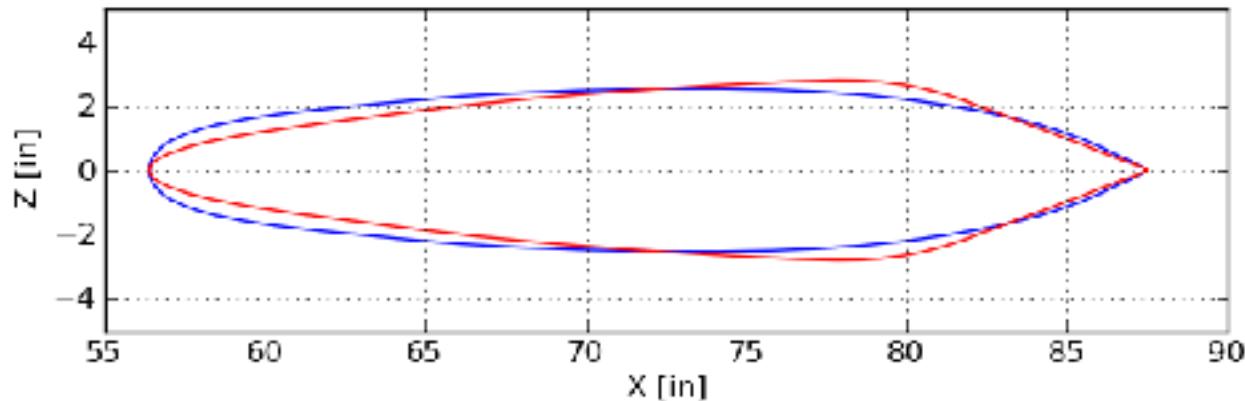


Side of Body Separation

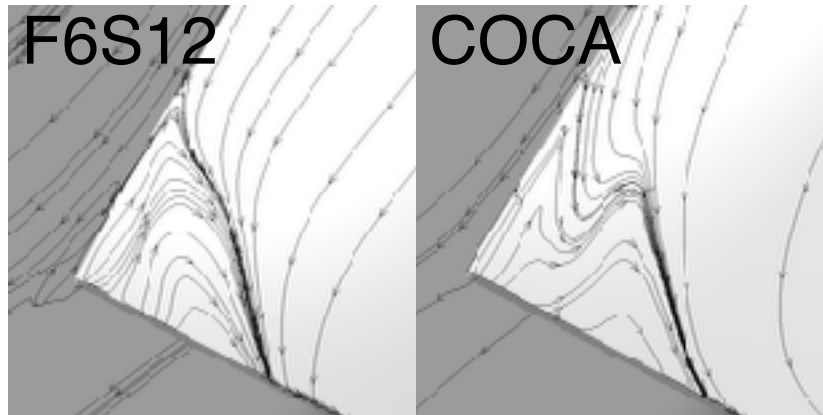


Wing  
Planform

# F6S12 — COCA



Blue: F6S12 w/horn, Red: COCA w/horn



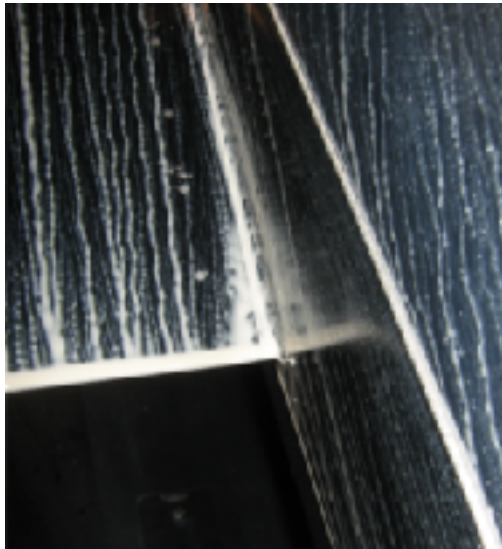
Side of Body Separation

Wing  
Planform

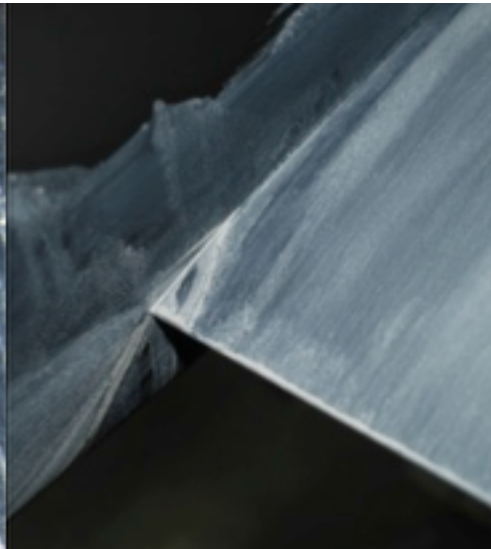
# Risk Reduction Tests



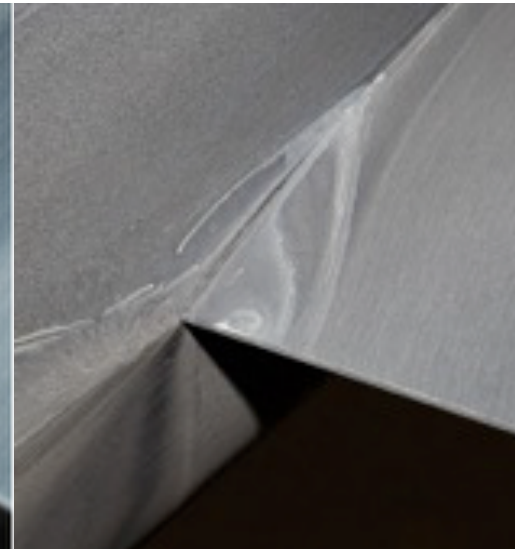
- Series of risk reduction tests
  - Ames TC2 3% wall mounted model, low RE
  - Virginia Tech 2.5% fullspan low RE
  - Langley 14x22 6% fullspan high RE
- CFD solutions were run concurrently with all tests



TC2

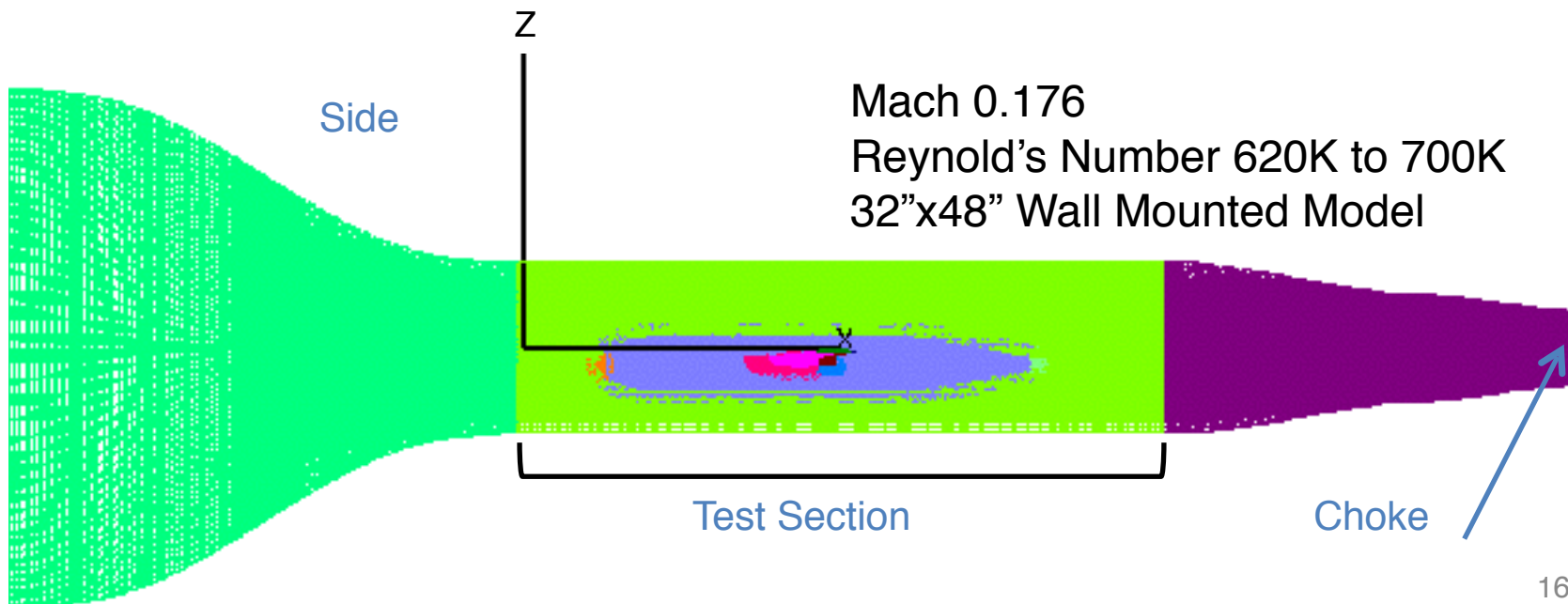
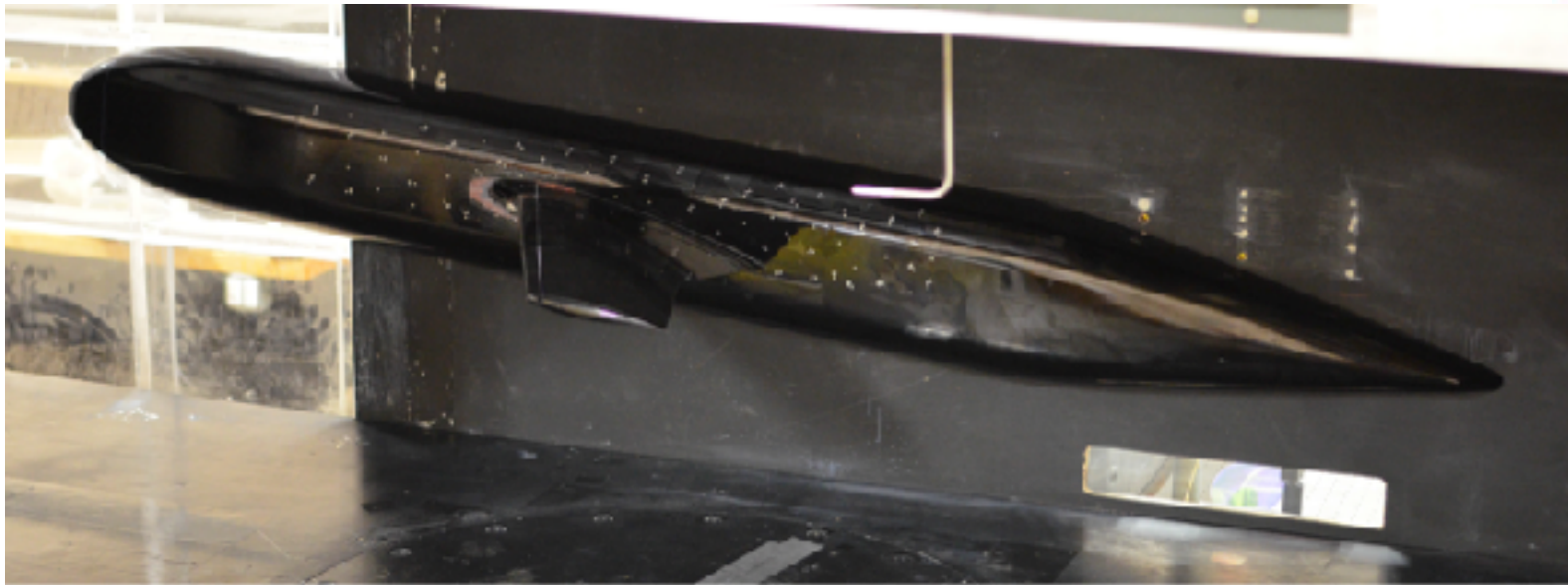


VA Tech

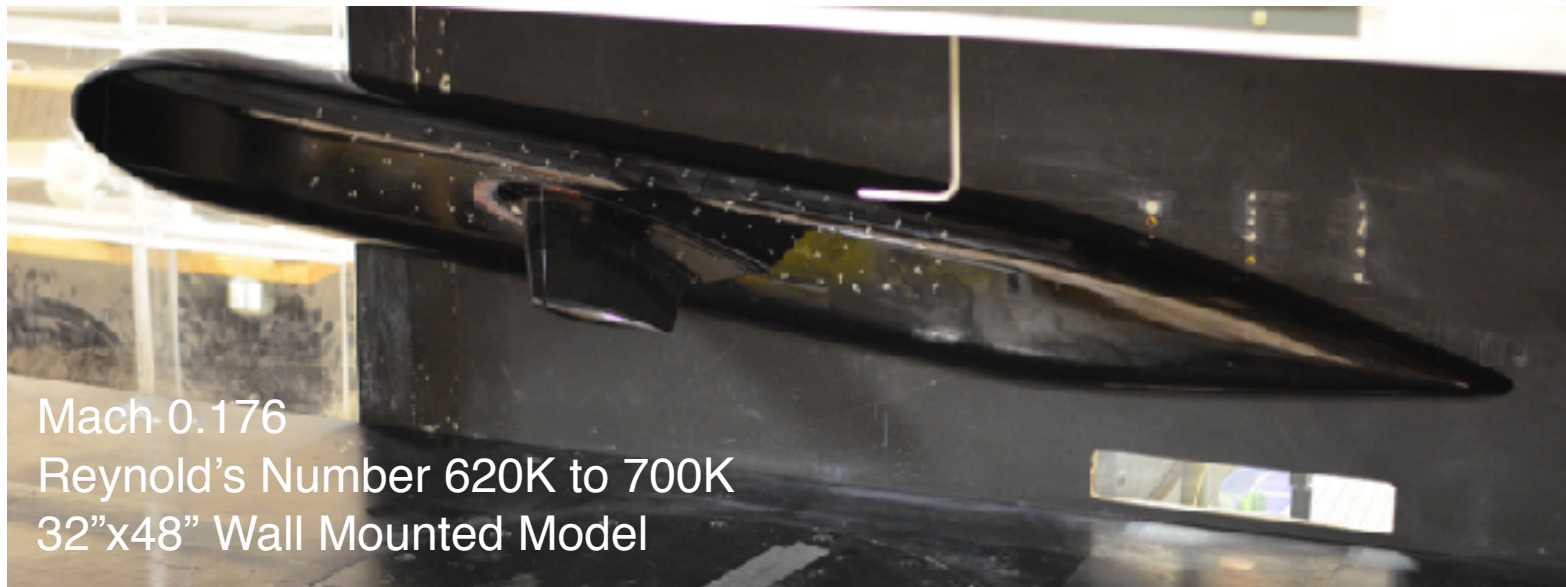


14x22

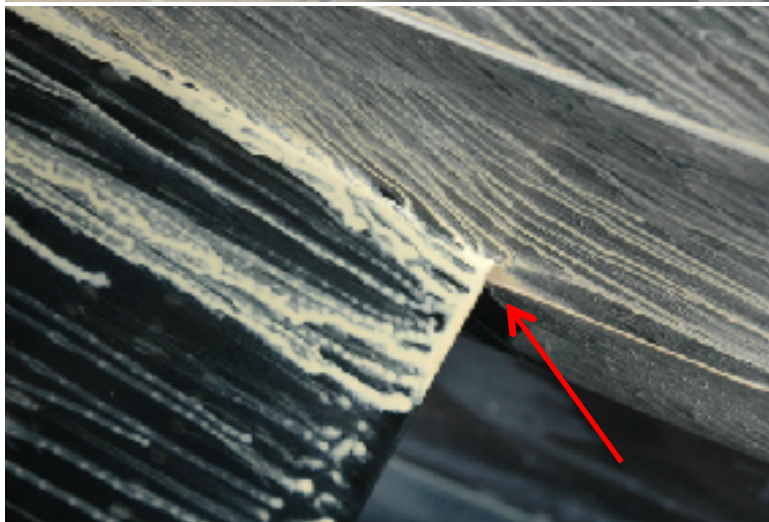
# Model in TC2 and CFD Geometry



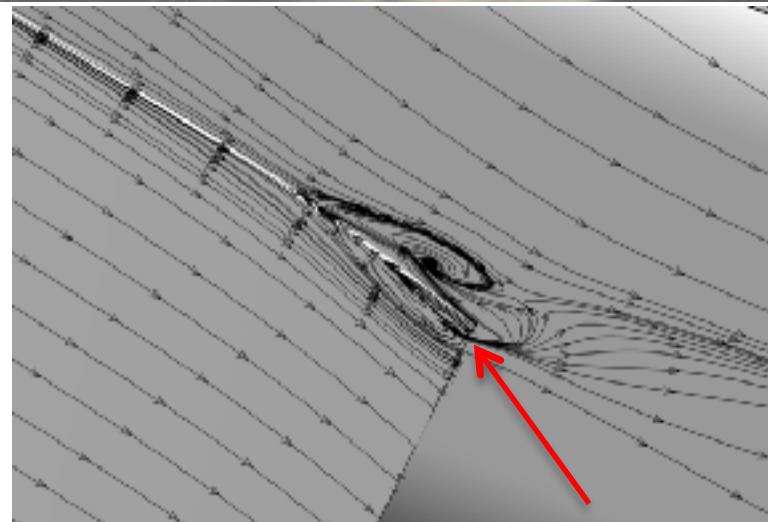
# TC2 Risk Reduction



Mach-0.176  
Reynold's Number 620K to 700K  
32"x48" Wall Mounted Model



Small hint of separation



Clear evidence separation

**Determined Wall Mounted model is not ideal for this test**

Results published in AIAA Paper 2016-1558

# Virginia Tech 2.5% Full Span Test

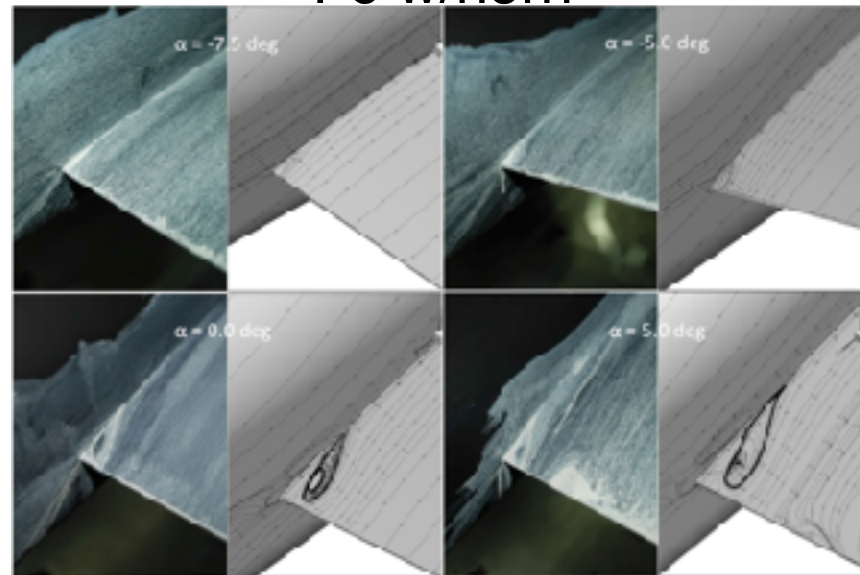


Mach 0.176, Reynolds Number of 620K, 6' Test Section

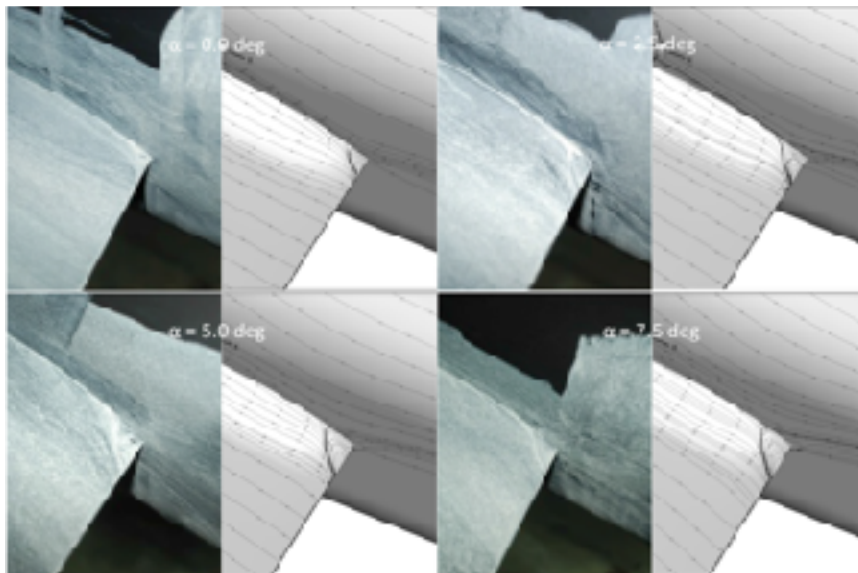
# VT Tunnel Risk Reduction



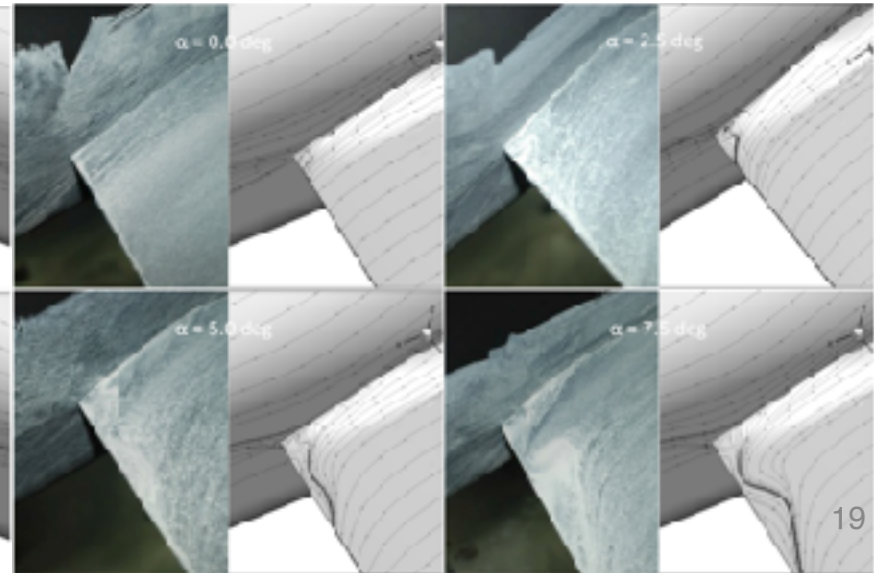
F6 w/horn



F6S12 w/horn



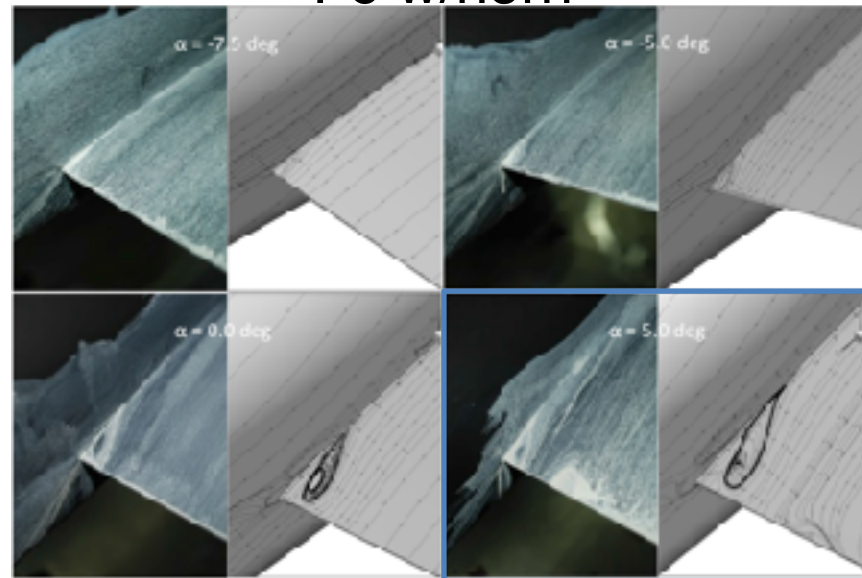
COCA w/horn



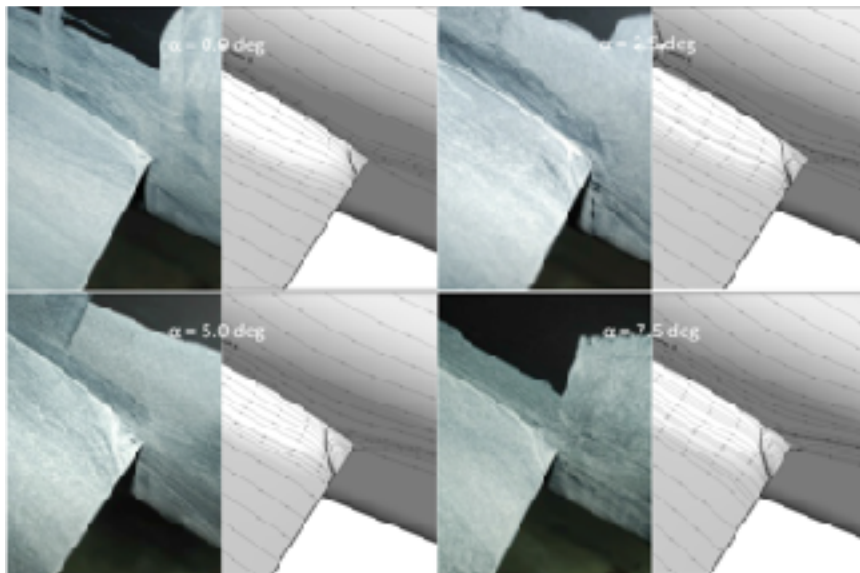
# VT Tunnel Risk Reduction



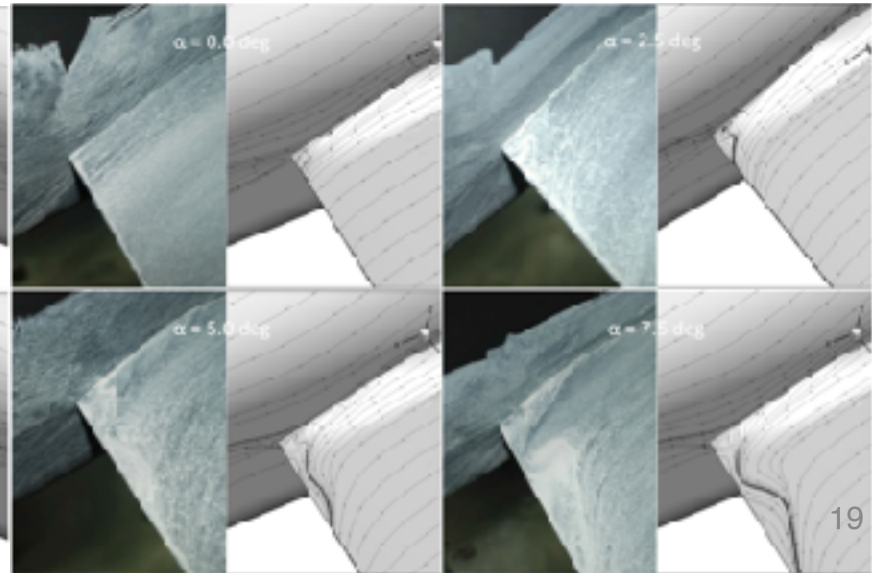
F6 w/horn



F6S12 w/horn



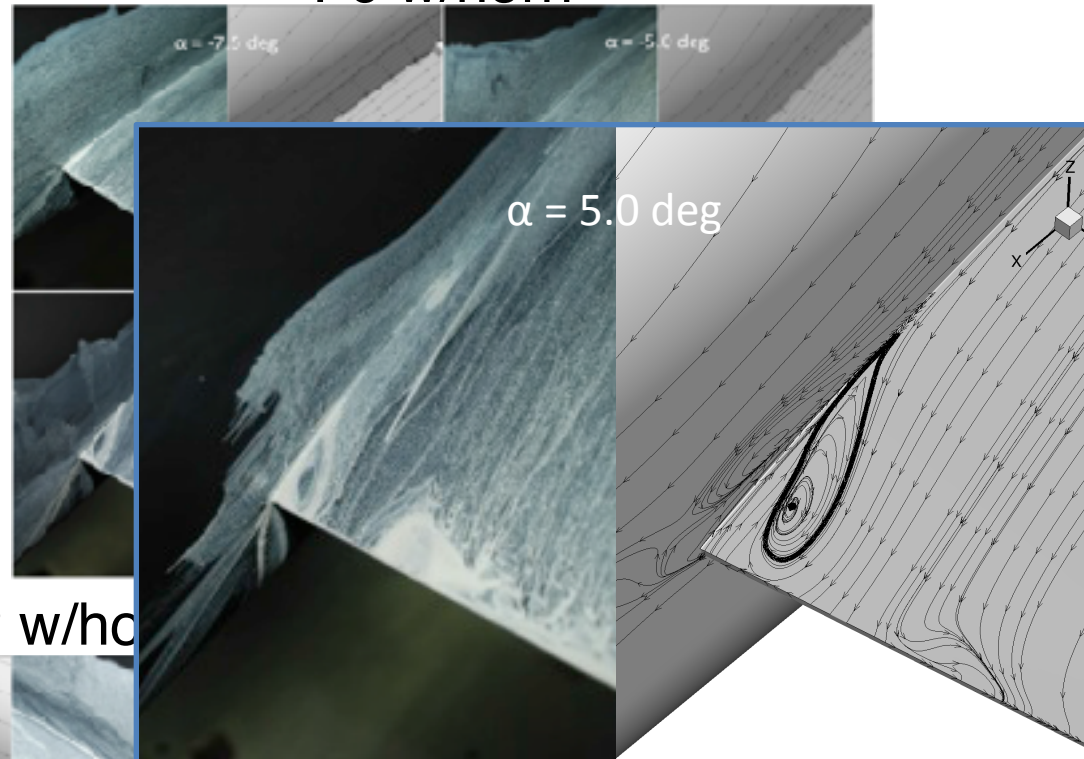
COCA w/horn



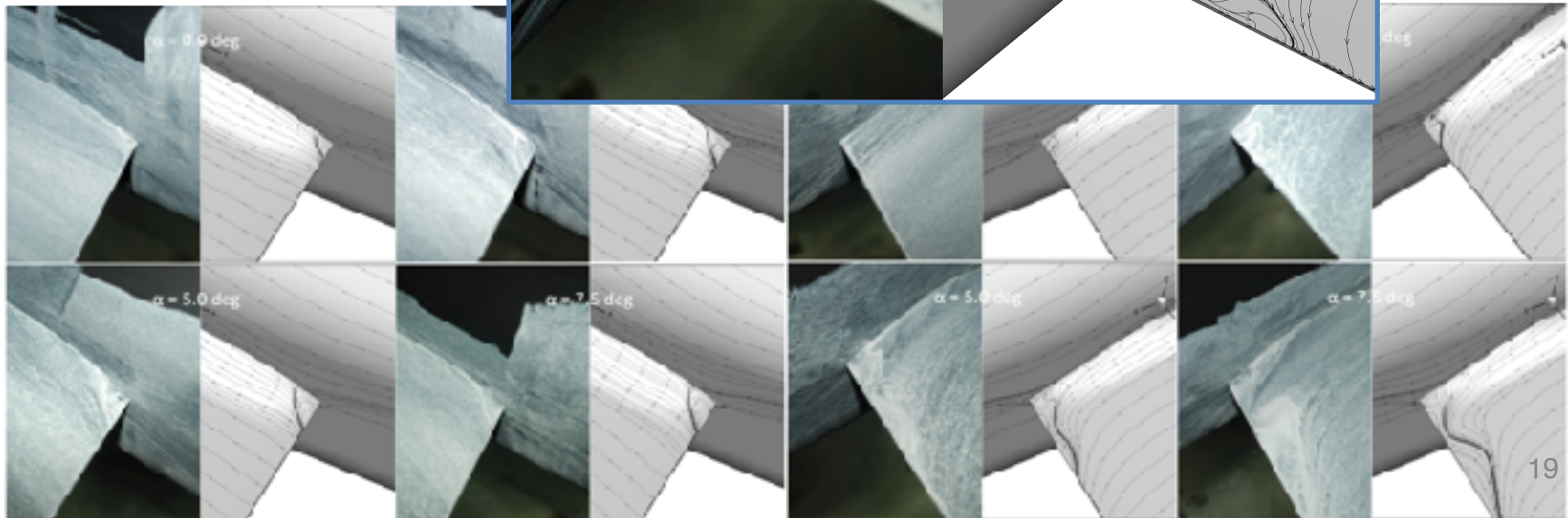
# VT Tunnel Risk Reduction



F6 w/horn



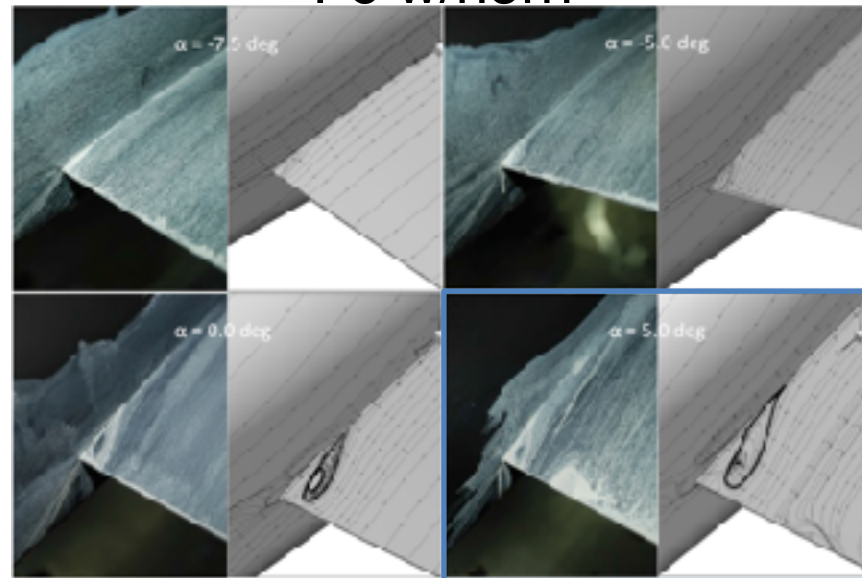
F6S12 w/horn



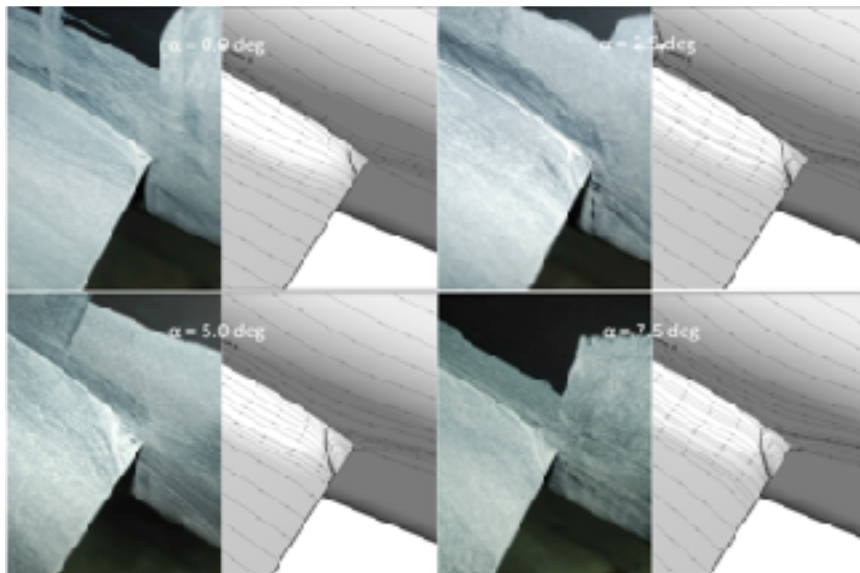
# VT Tunnel Risk Reduction



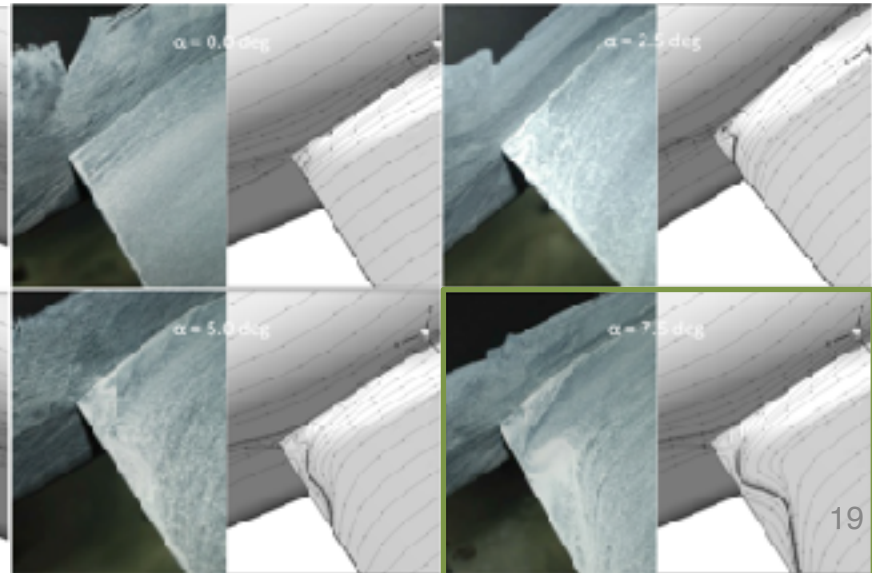
F6 w/horn



F6S12 w/horn



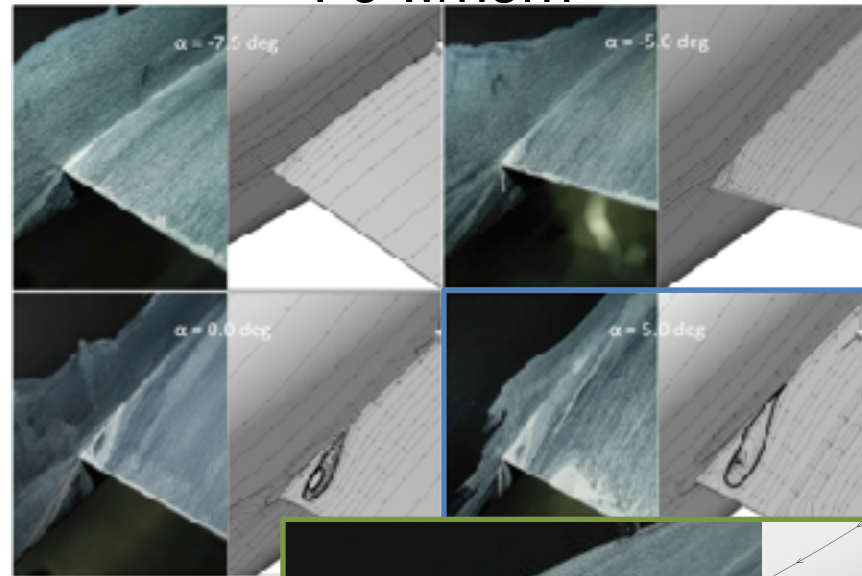
COCA w/horn



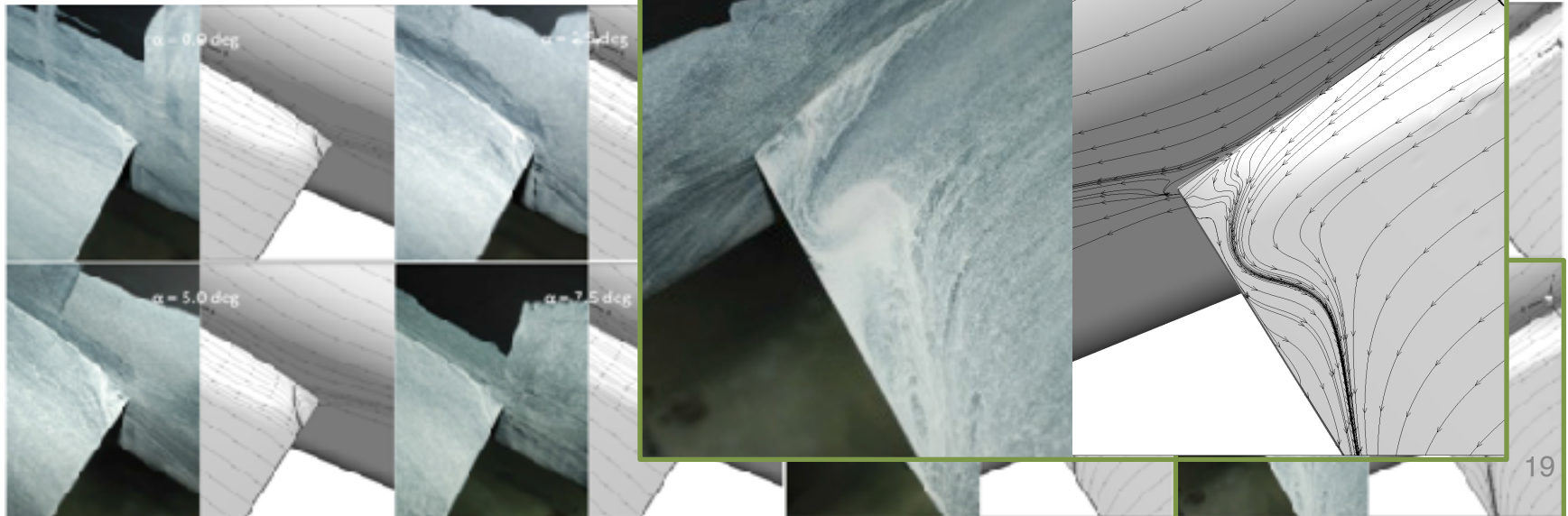
# VT Tunnel Risk Reduction



F6 w/horn



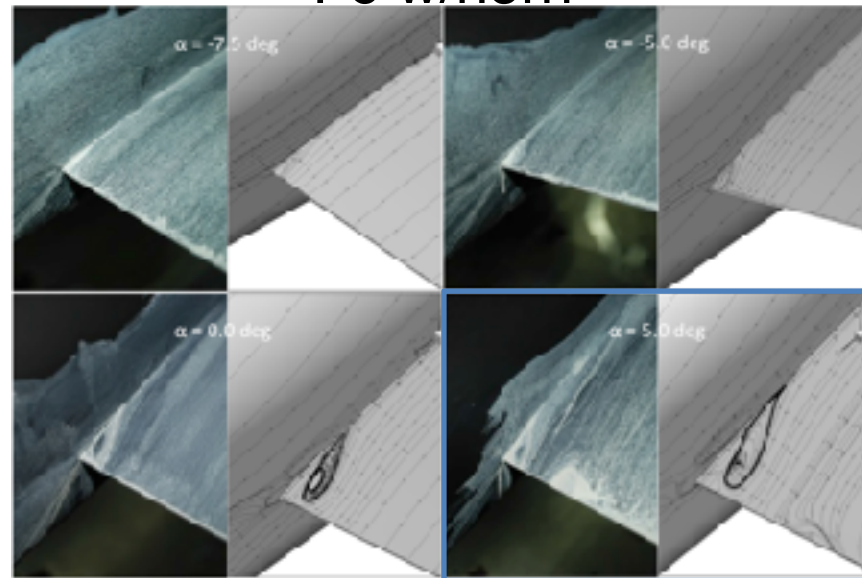
F6S12 w/horn



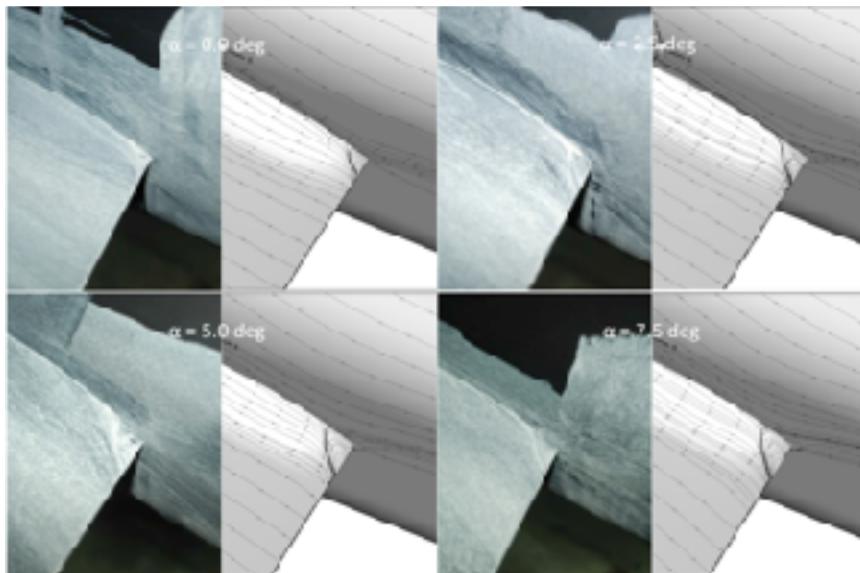
# VT Tunnel Risk Reduction



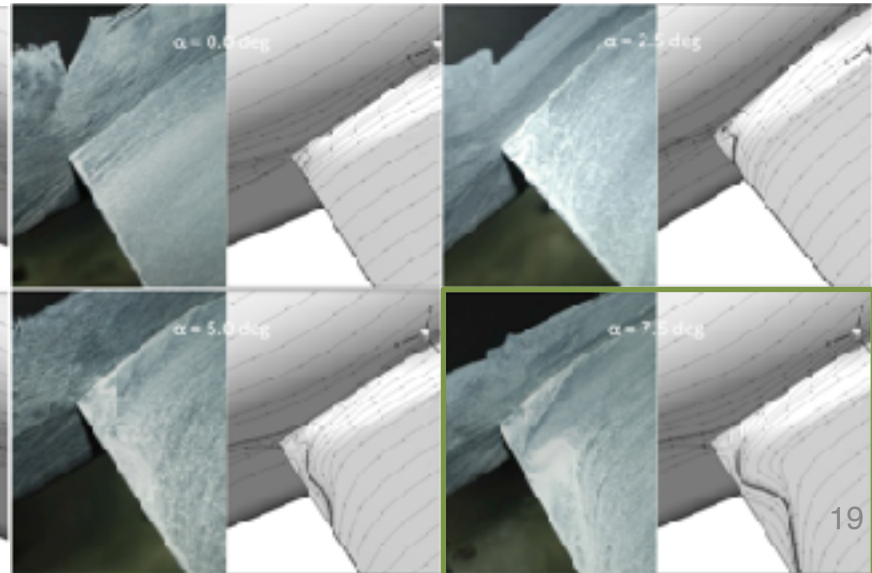
F6 w/horn



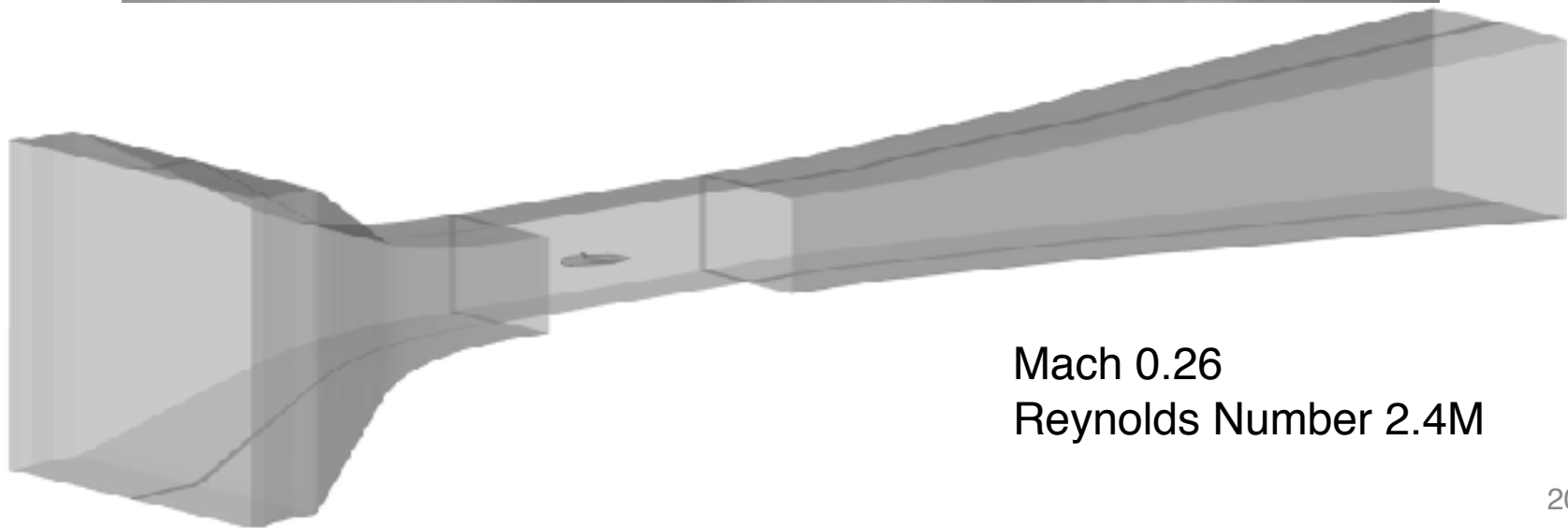
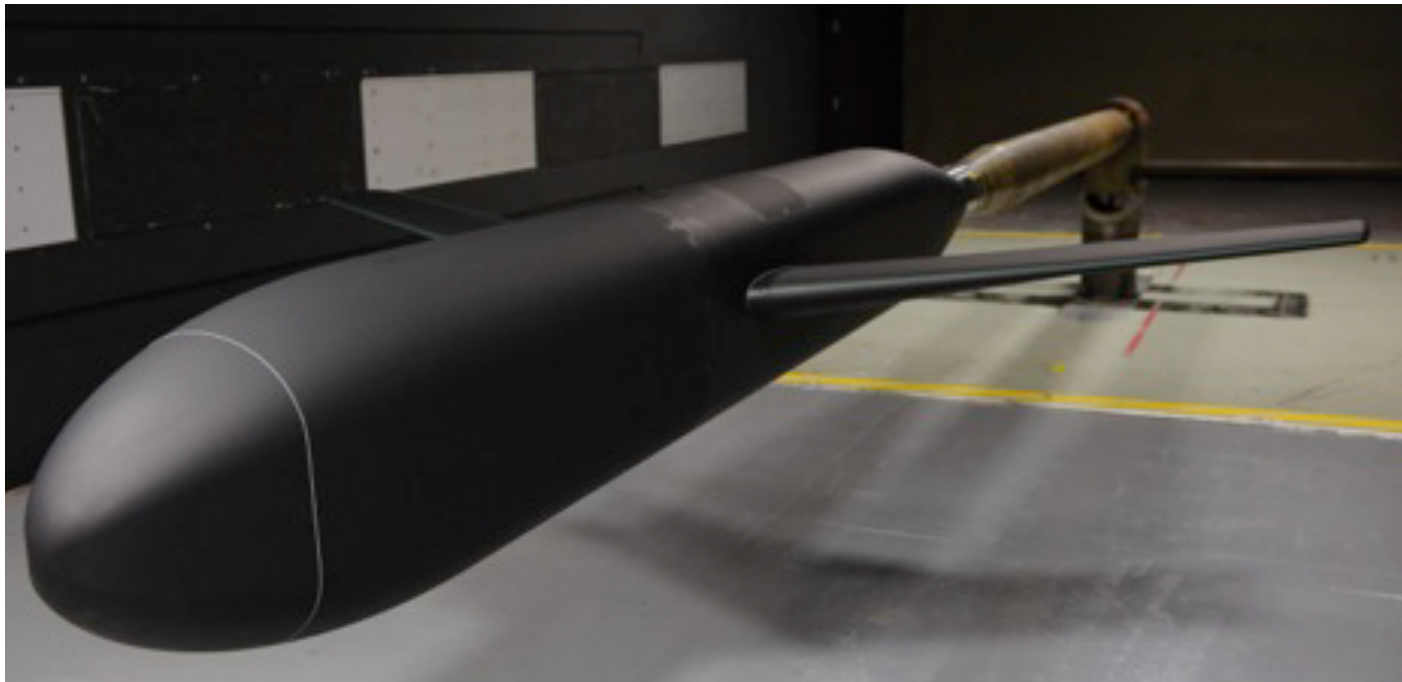
F6S12 w/horn



COCA w/horn



# 14x22 6% Risk Reduction Test



Mach 0.26  
Reynolds Number 2.4M

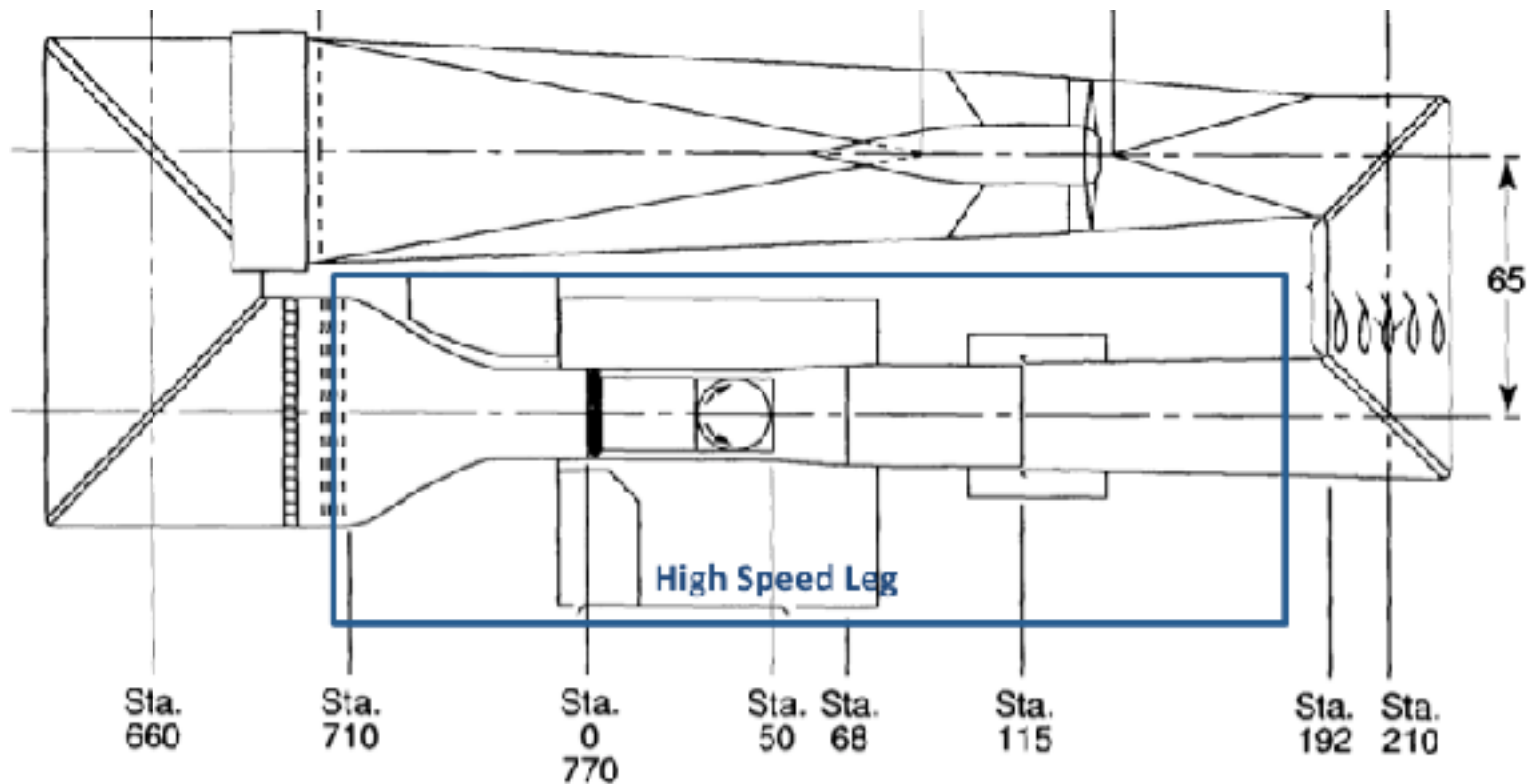
# 14x22 6% Risk Reduction Setup



- Three data sources
  - Experiment
  - CFD in Free Air
  - CFD with 14x22 wind tunnel walls
- Comparisons: oil flow vs streamlines
- Additional results for  $\alpha = -10.0 - 10.0$  degrees in paper
- Additional experimental results in NASA TM-219348

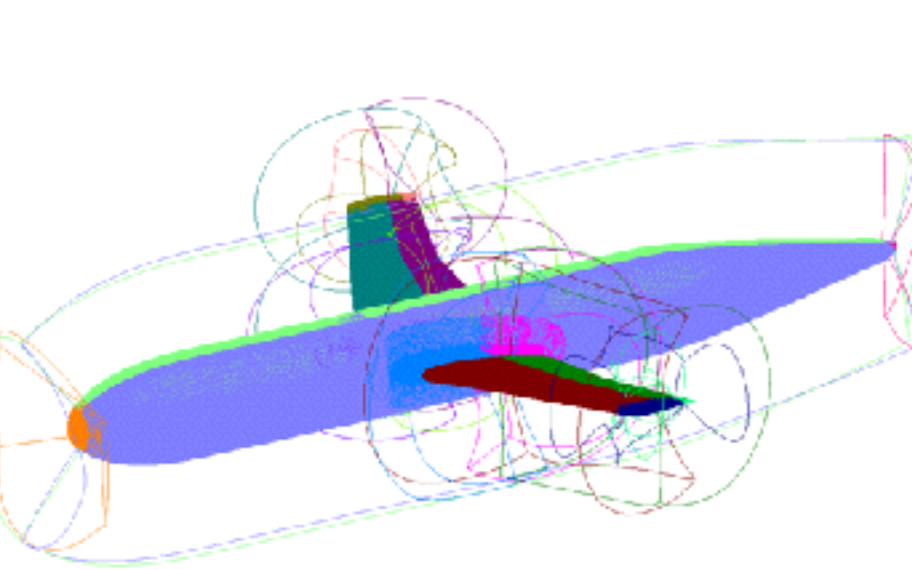


- 14.5 ft high by 21.75 ft wide test section
- Closed-circuit wind tunnel
- Blue box represents high speed leg
- RE = 2.4 million, Mach 0.26

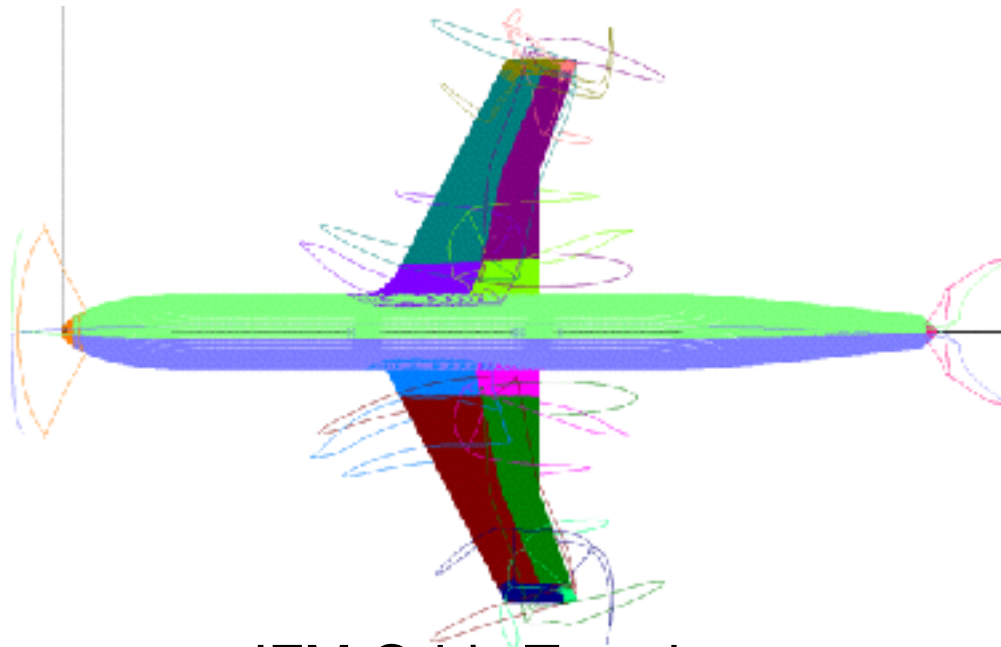


# Juncture Flow Model Grids

- Grids created based on best practices, as defined by AIAA workshops (DPW, HiLift, etc)
- Grid resolution study was performed early on to establish grid guidelines for all cases



JFM Grids ISO-view

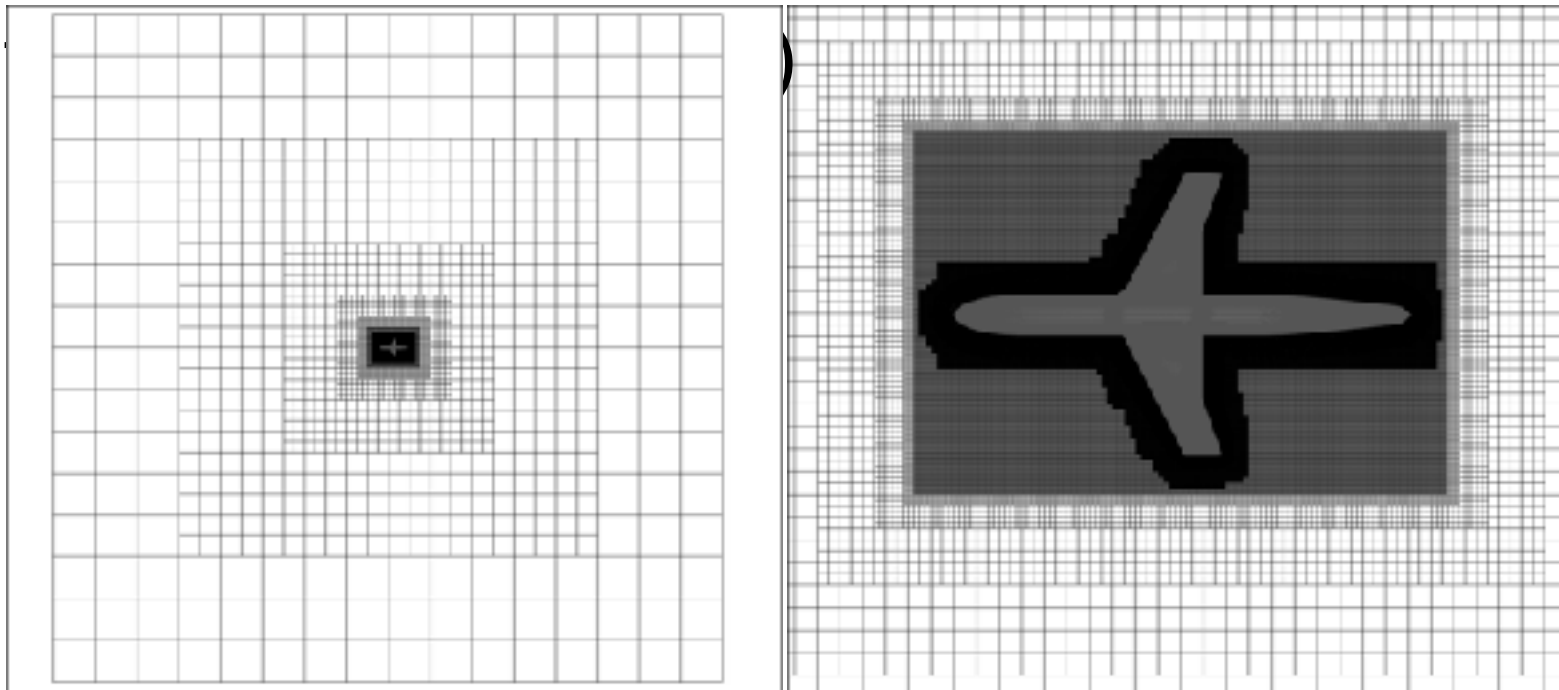


JFM Grids Top-view

# JFM Free Air Cases



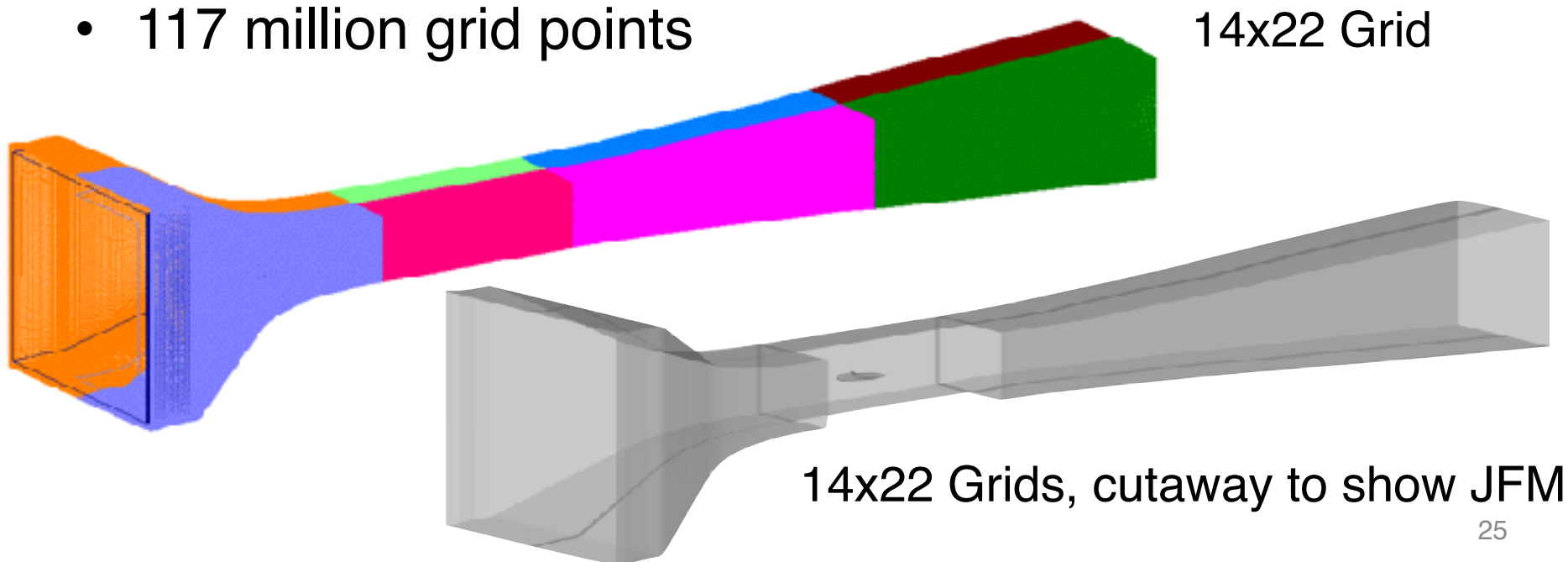
- JFM grids, imbedded in Overflow's off body grids
- Fairfield at 100 chord lengths away
- 108 Million grid points
- 420 Intel Broadwell cores, 12 hours wall



# JFM Wind Tunnel Cases



- JFM grids, installed in the 14x22 wind tunnel grids
- Inflow BC: Stagnation pressure/temperature
- Outflow BC: Back pressure iterated to match tunnel speed.
- 1200 Intel Ivy Bridge cores, 60-120 hours wall time (NASA Pleiades)
- 117 million grid points

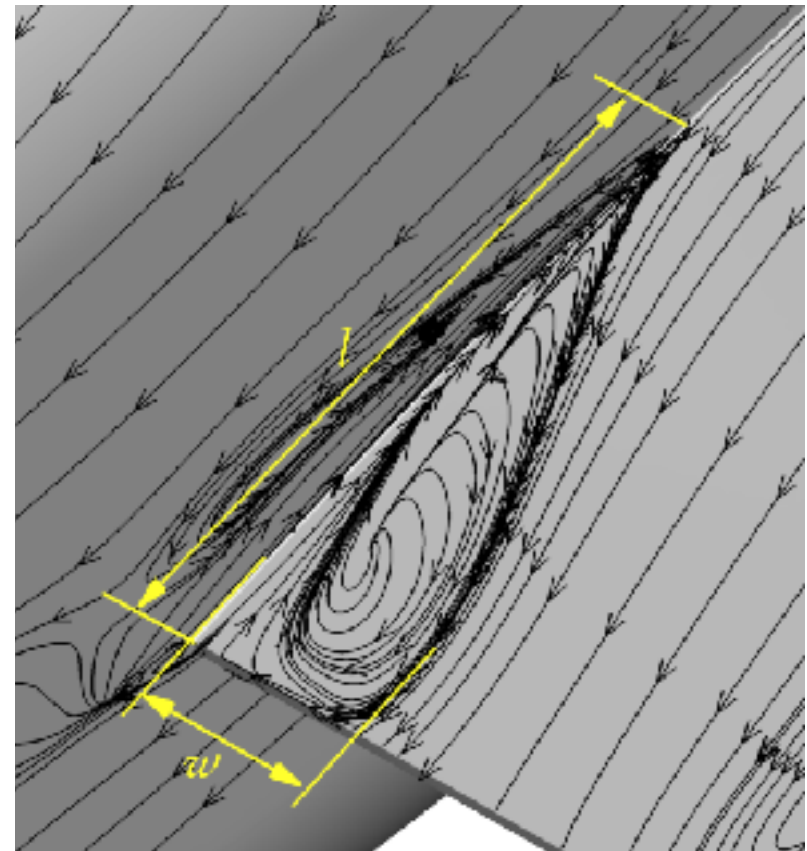
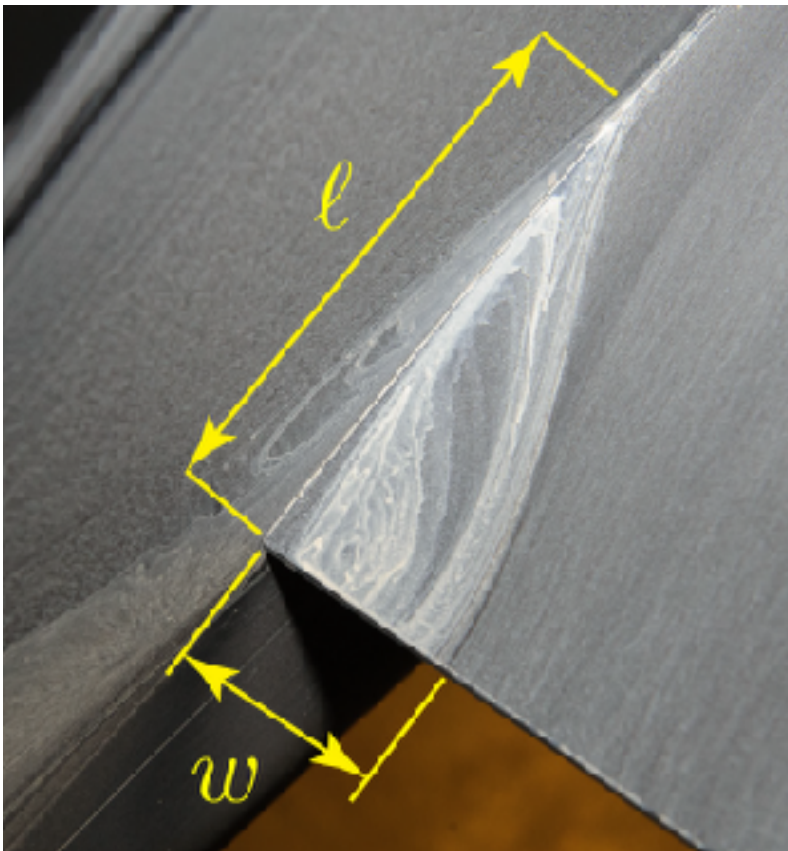


# SOB Bubble Size Definitions



Experiment Oil Flow

CFD Surface Streamlines

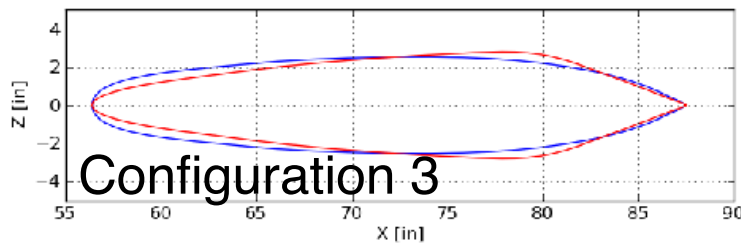
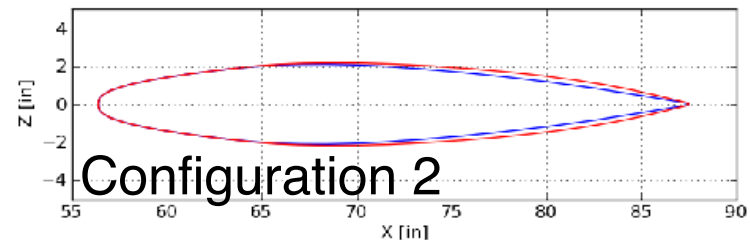
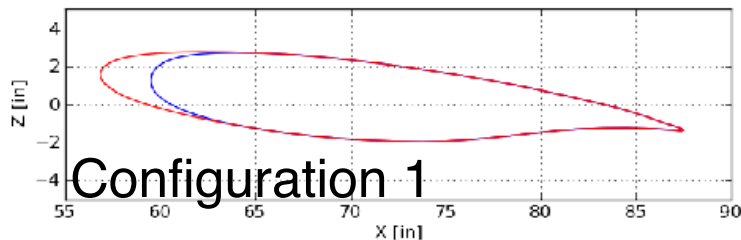


length  $l$  and width  $w$  bubble size definitions

# Wing Configurations



Configuration	Port Wing	Starboard Wing	Data
1	F6 no horn	F6 w/horn	Exp, CFD Free Air, CFD WT
2	NACA 0015 w/horn	NACA 0015mod w/horn	Exp, CFD Free Air, CFD WT
3	F6S12 w/horn	COCA w/horn	Exp, CFD Free Air

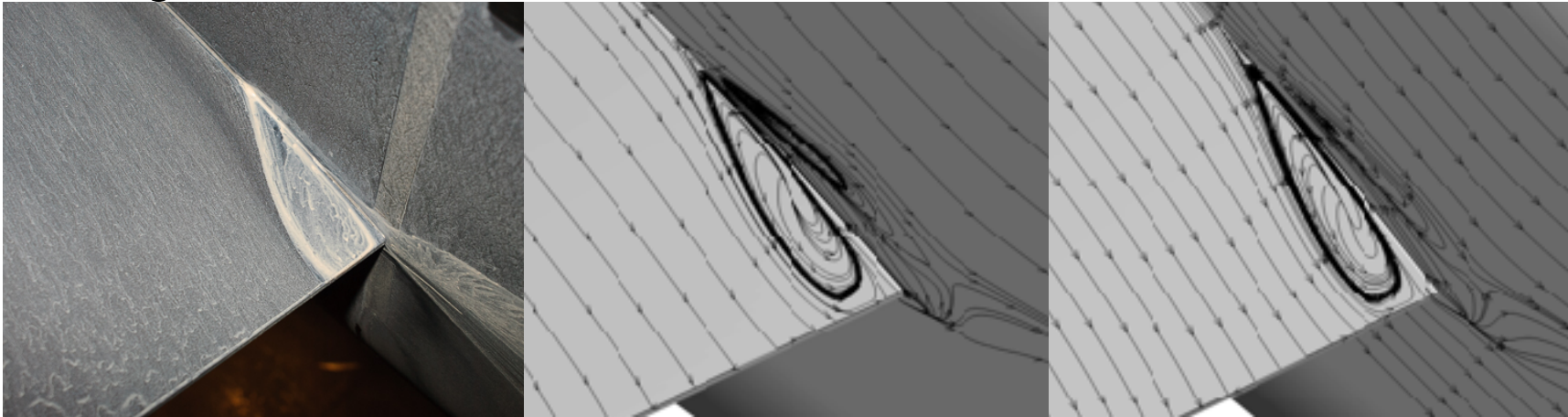


— Port Wing (blue)  
— Starboard Wing (red)

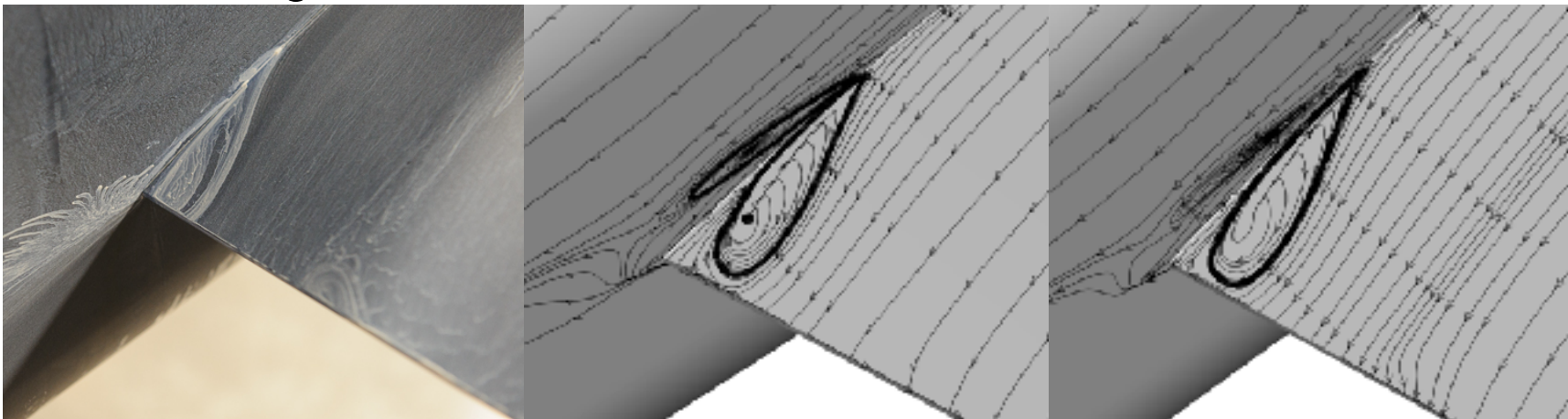
# Configuration 1: F6 no horn—F6 w/horn, $\alpha=5.0^\circ$



Port Wing: F6 no horn



Starboard Wing: F6 w/horn



Experiment

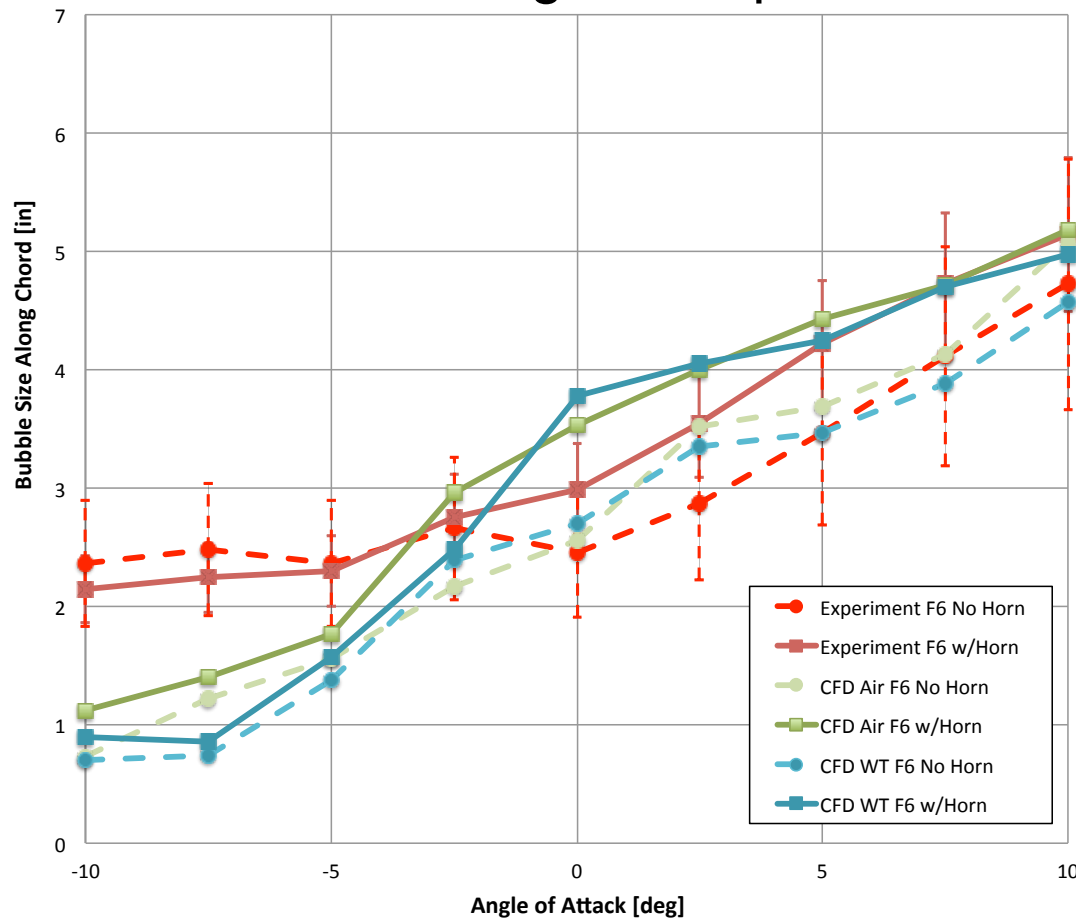
CFD Free Air

CFD WT

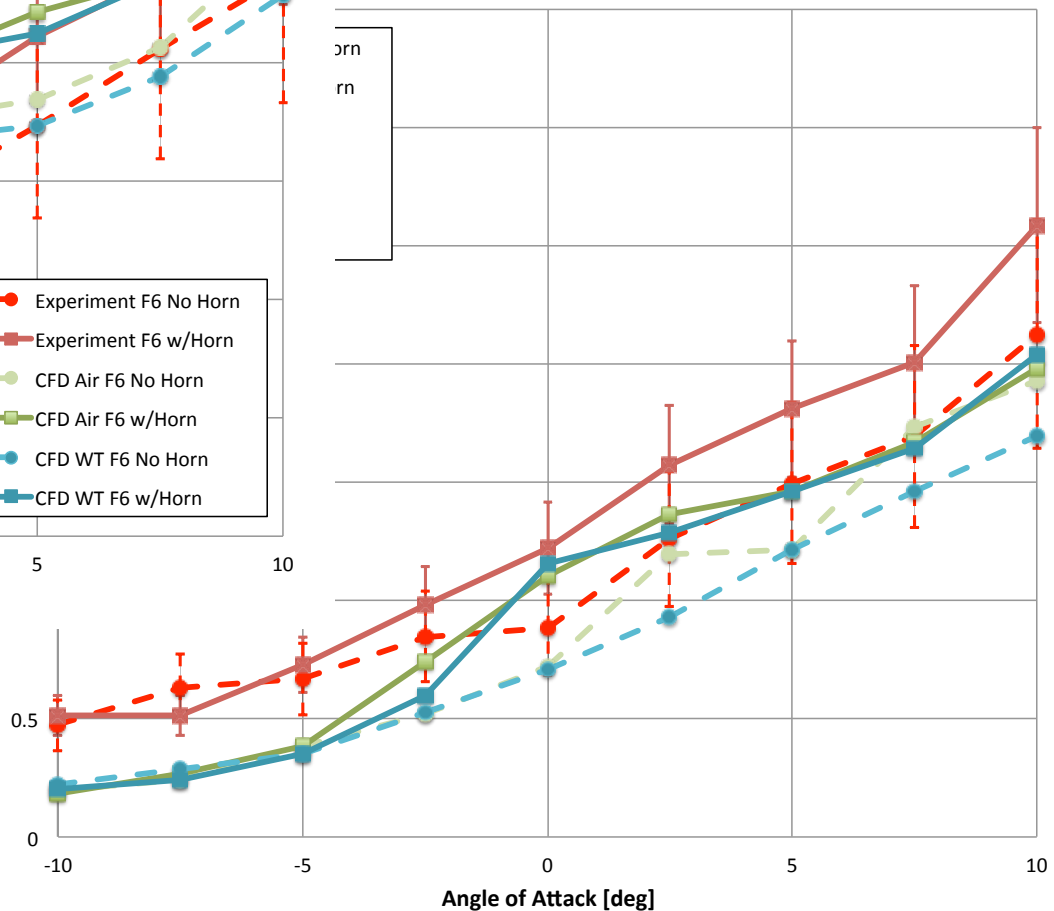
# Configuration 1: F6 no horn—F6 w/horn



## Bubble Length Comparison



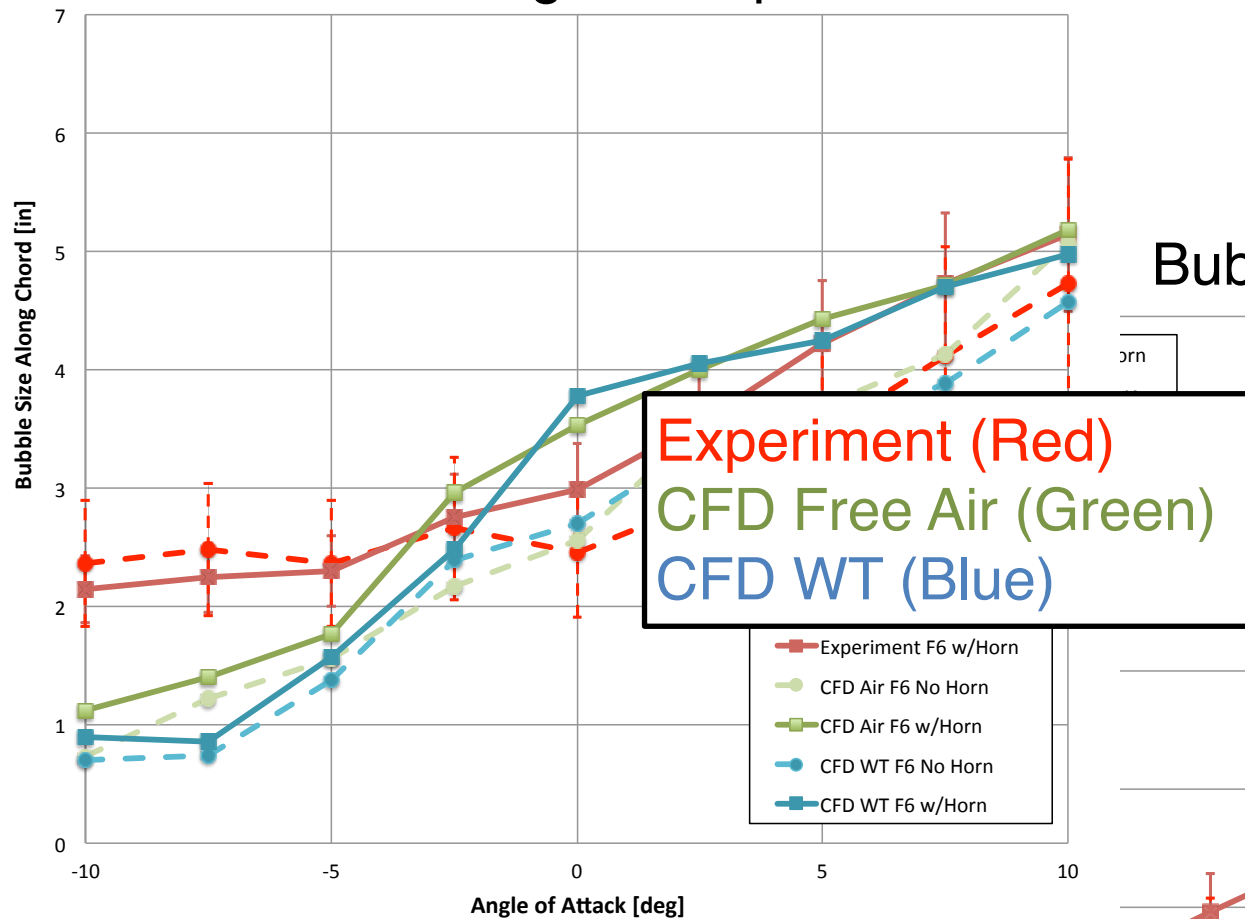
## Bubble Width Comparison



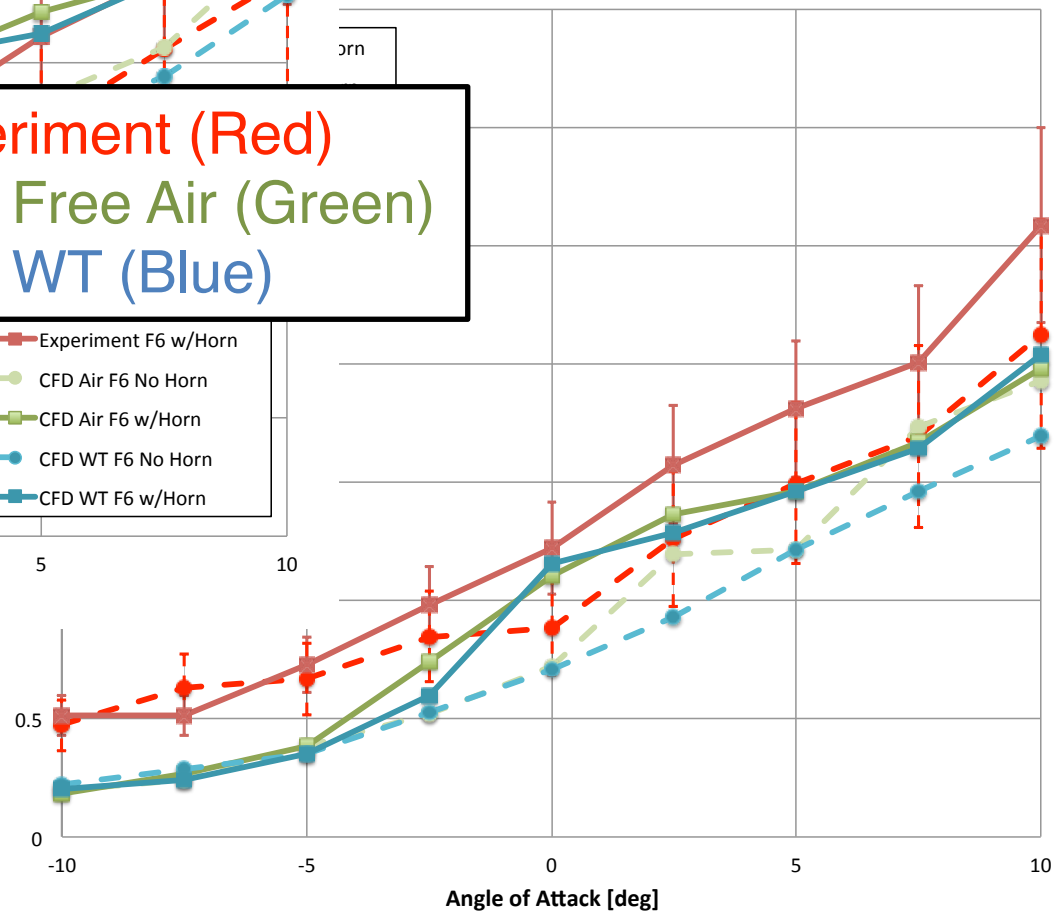
# Configuration 1: F6 no horn—F6 w/horn



## Bubble Length Comparison



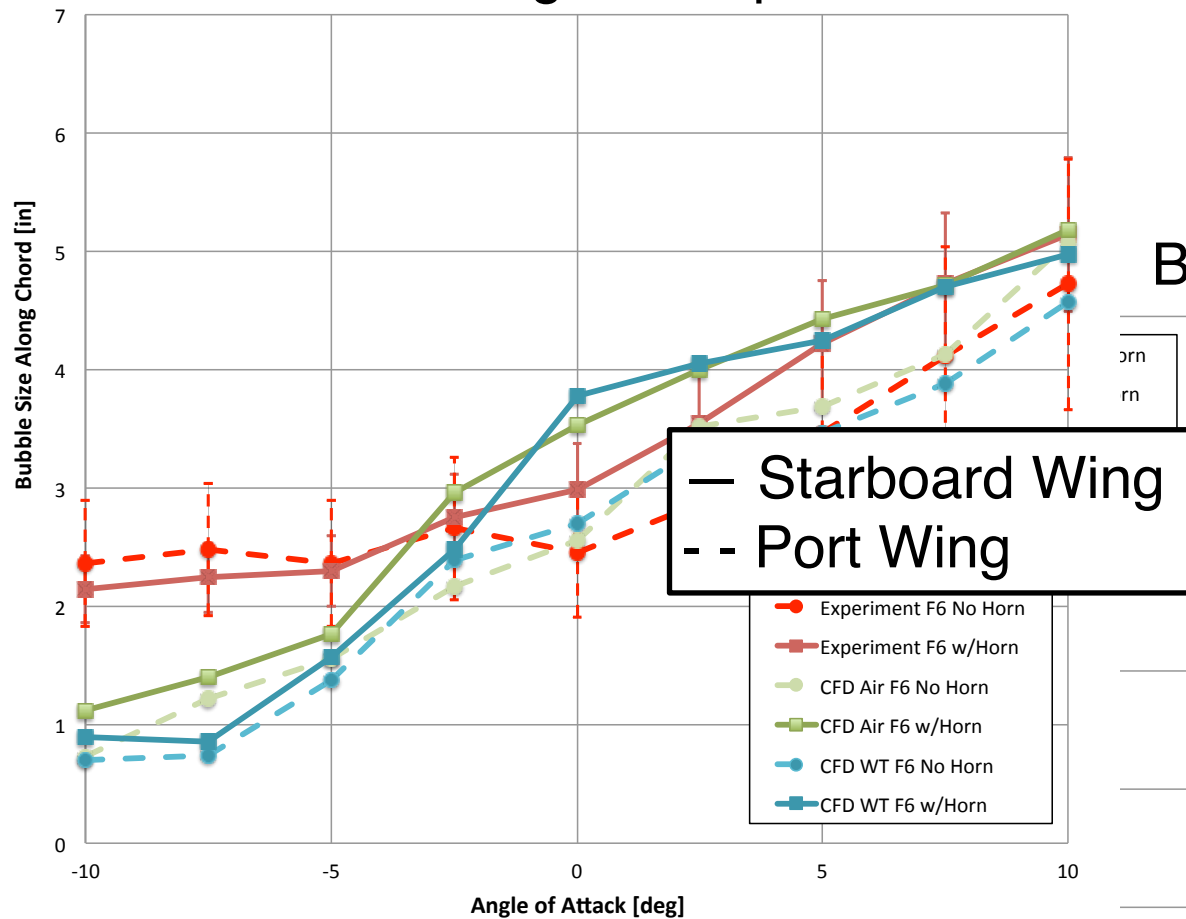
## Bubble Width Comparison



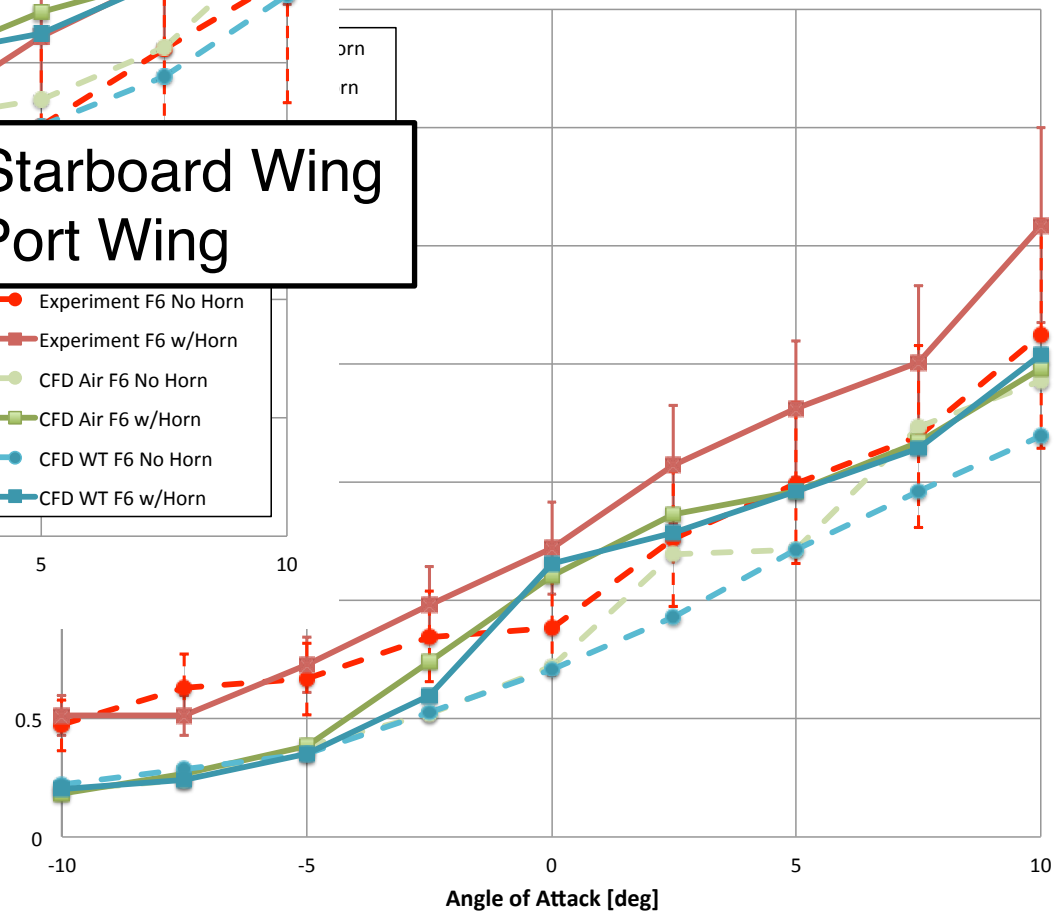
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## Bubble Length Comparison



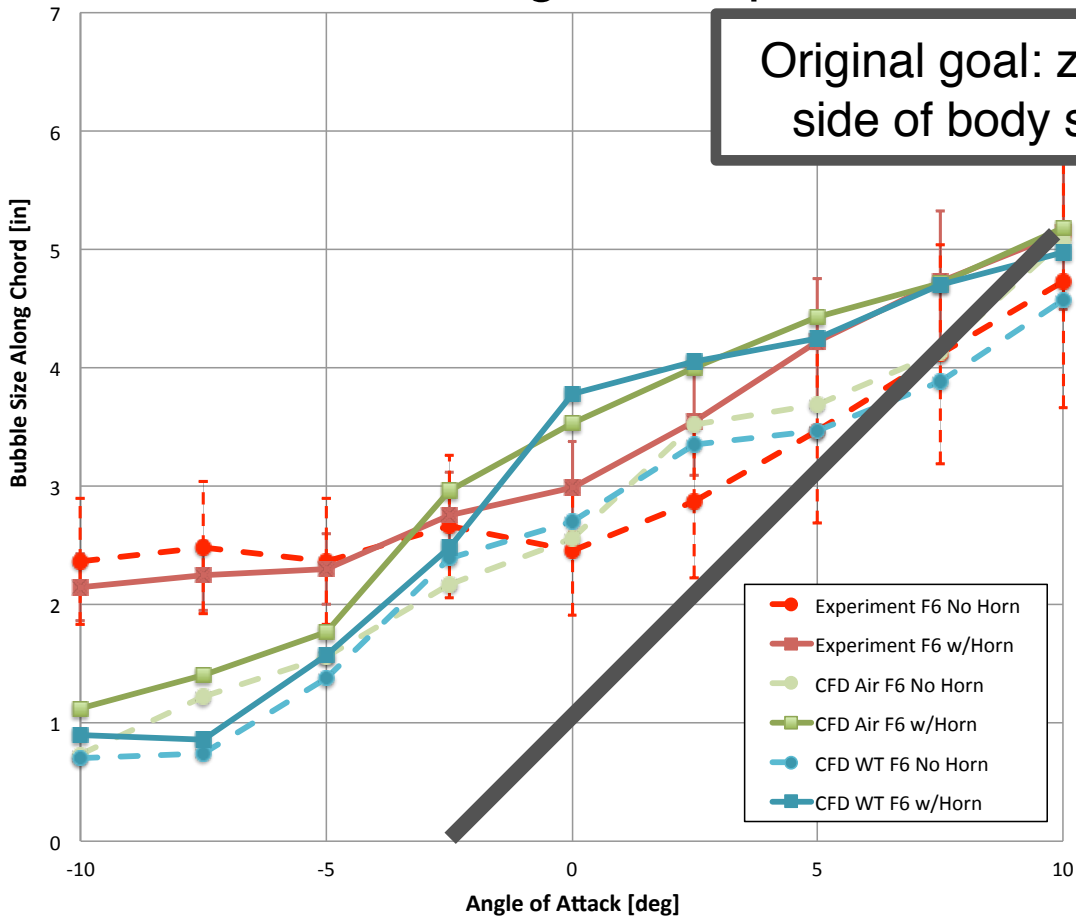
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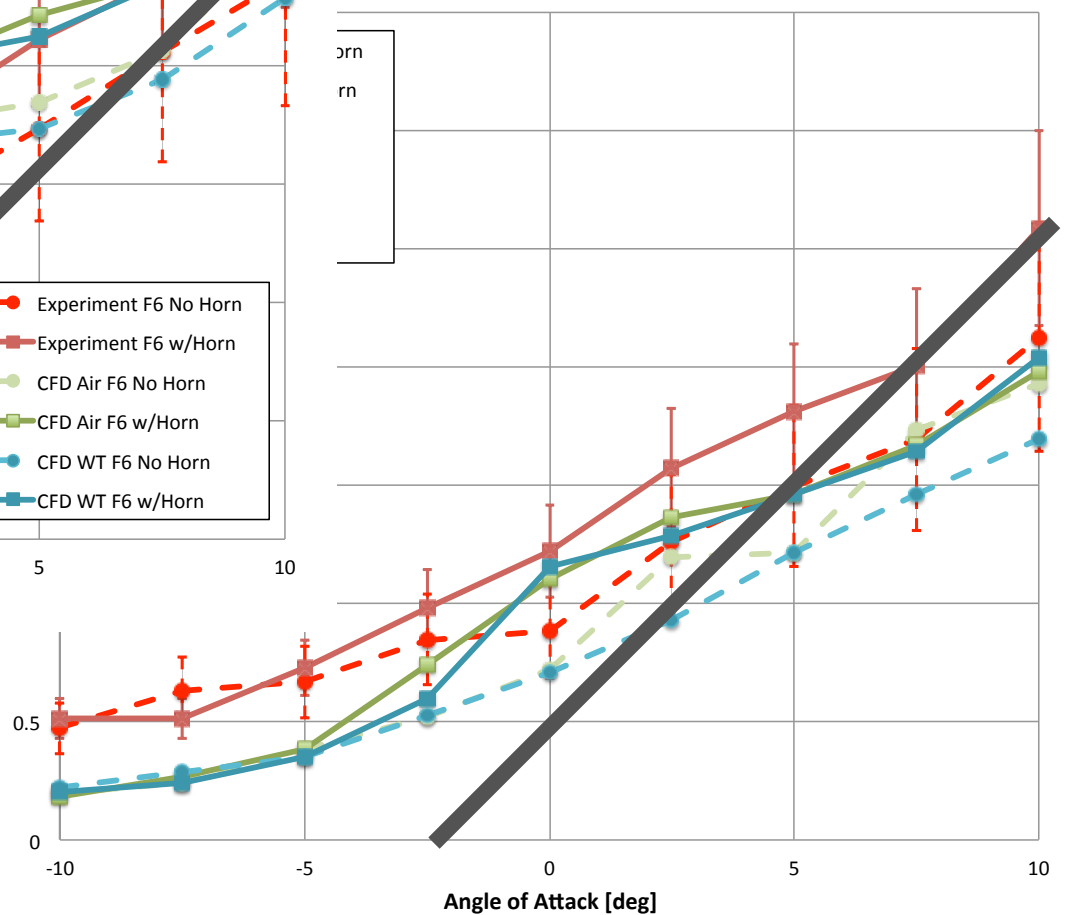


# Configuration 1: F6 no horn—F6 w/horn

## Bubble Length Comparison



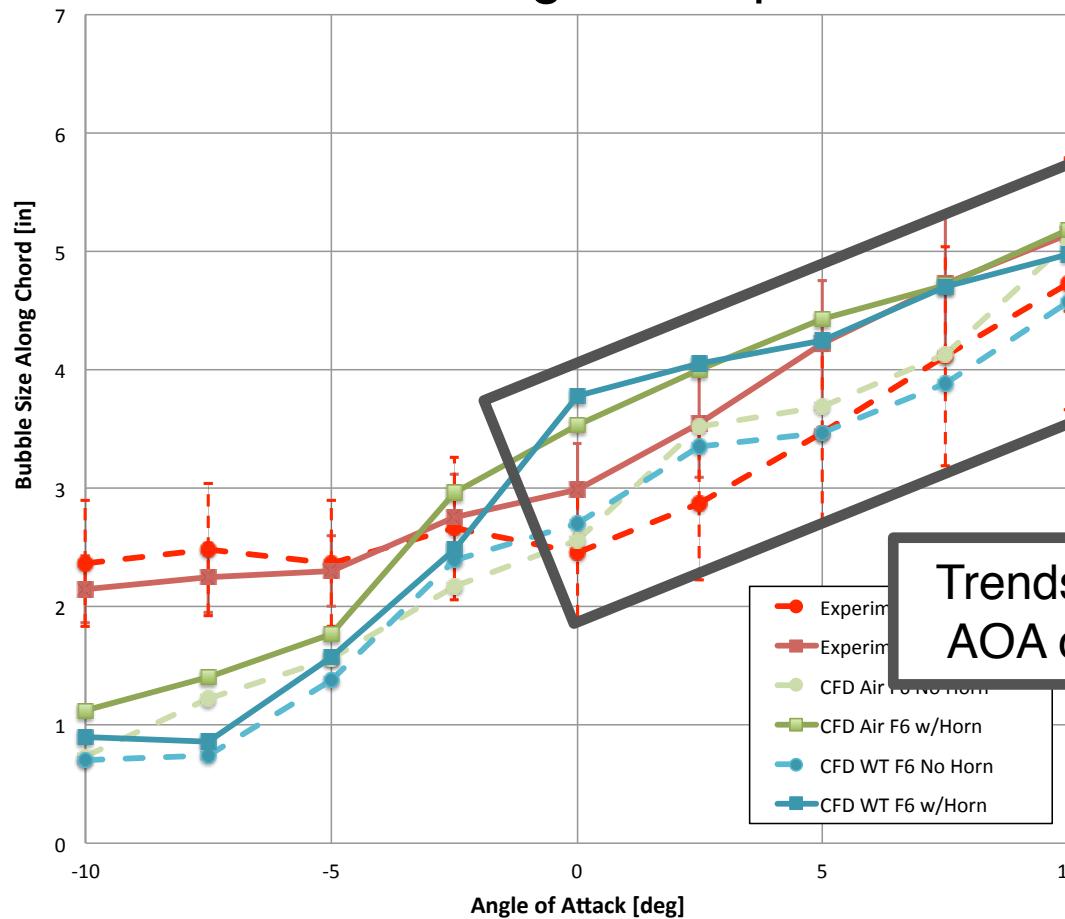
## Bubble Width Comparison



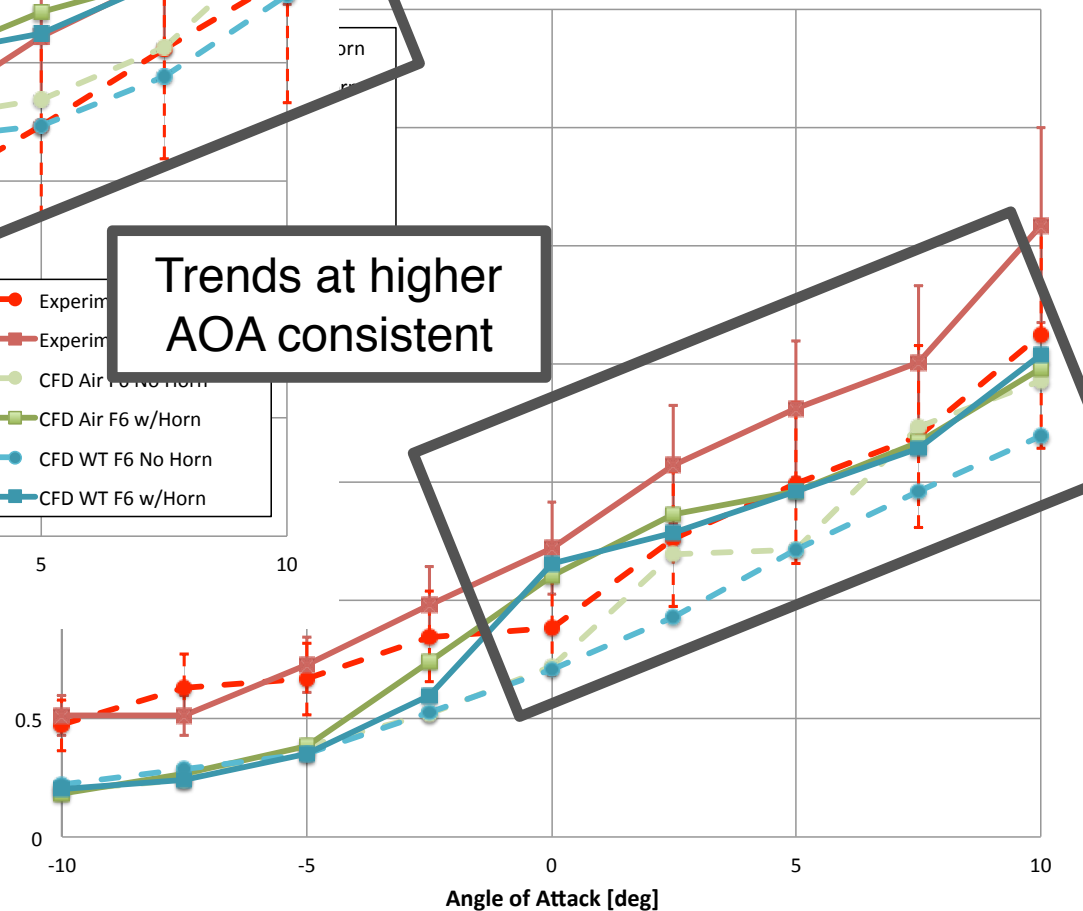
# Configuration 1: F6 no horn—F6 w/horn



## Bubble Length Comparison



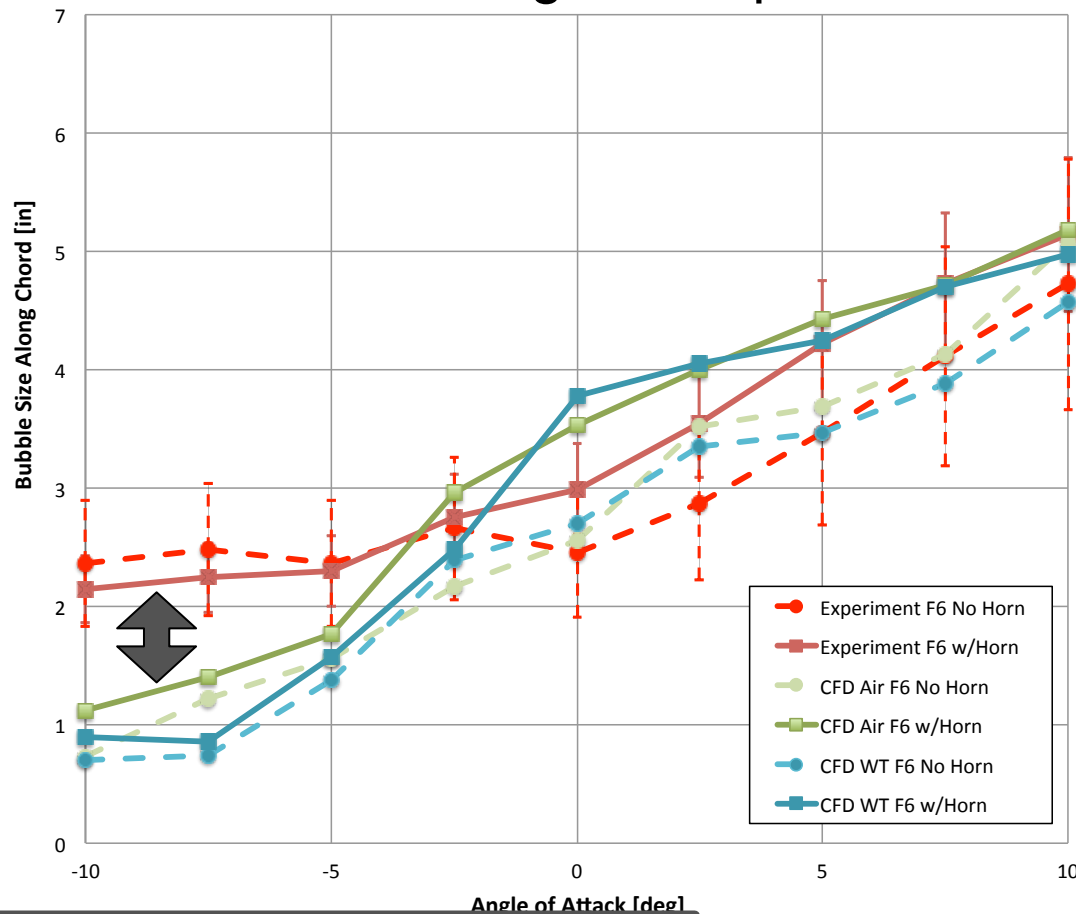
## Bubble Width Comparison





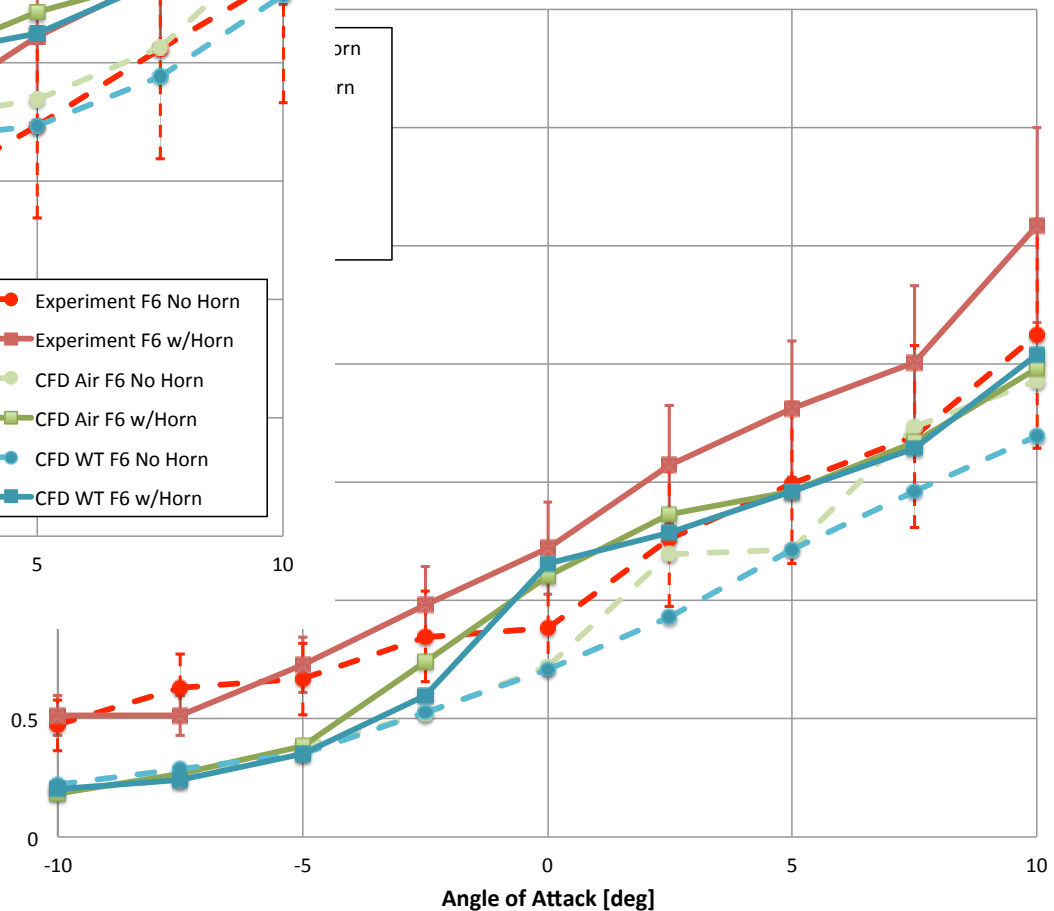
# Configuration 1: F6 no horn—F6 w/horn

## Bubble Length Comparison



Larger difference between CFD and WT Data at lower AOA. Bubble size doesn't go to zero

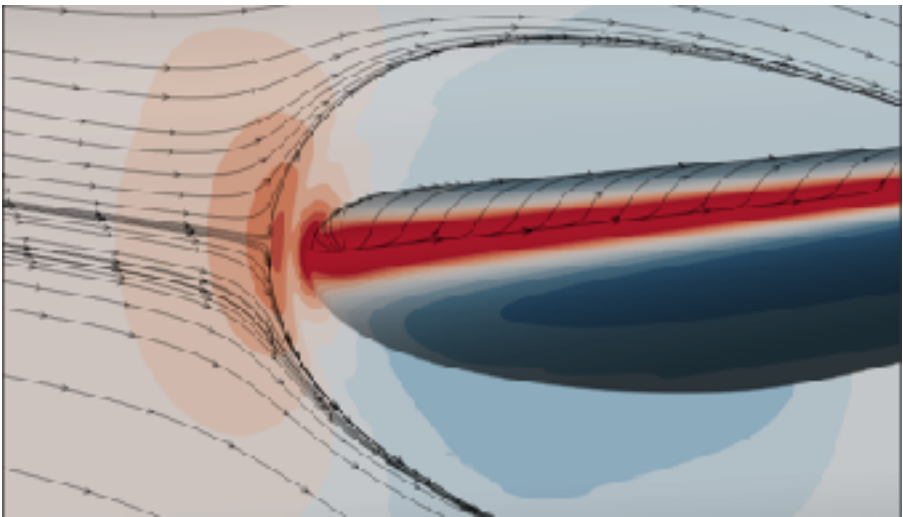
## Bubble Width Comparison



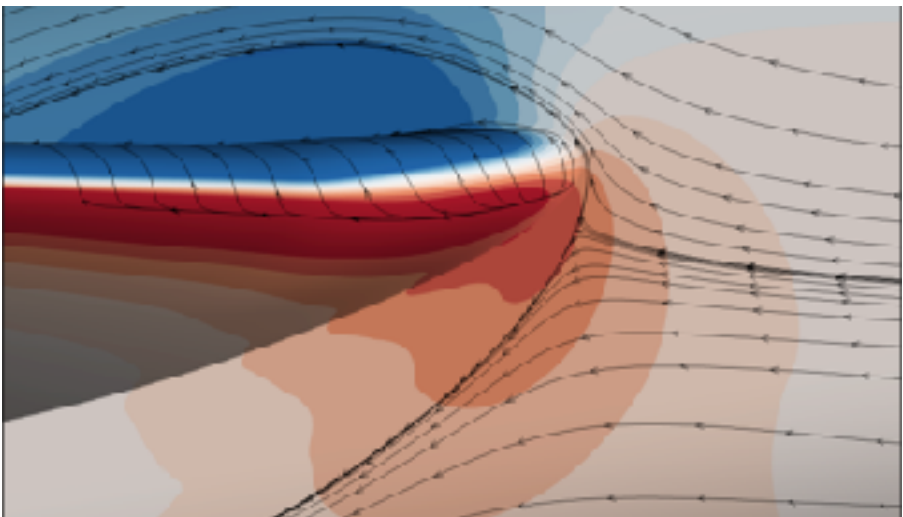
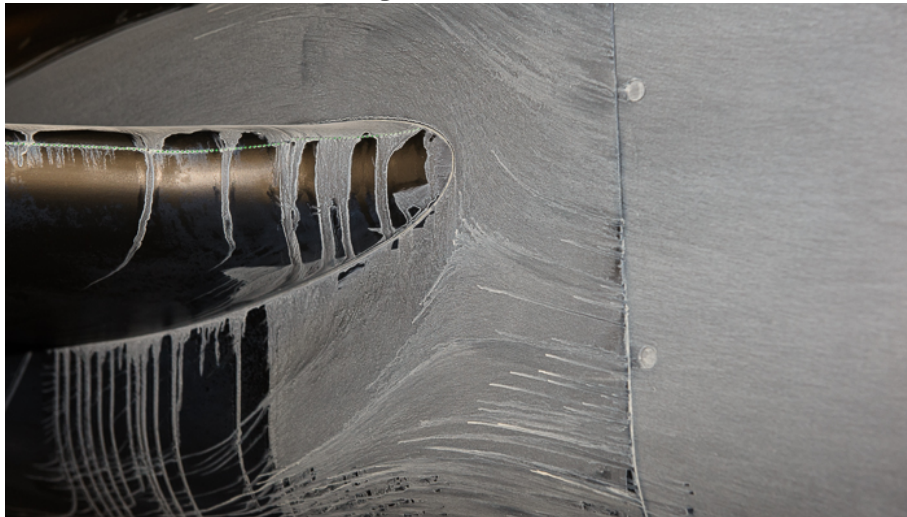
# Configuration 1: F6 no horn—F6 w/horn, $\alpha=5.0^\circ$ LE



Port Wing: F6 no horn



Starboard Wing: F6 w/horn



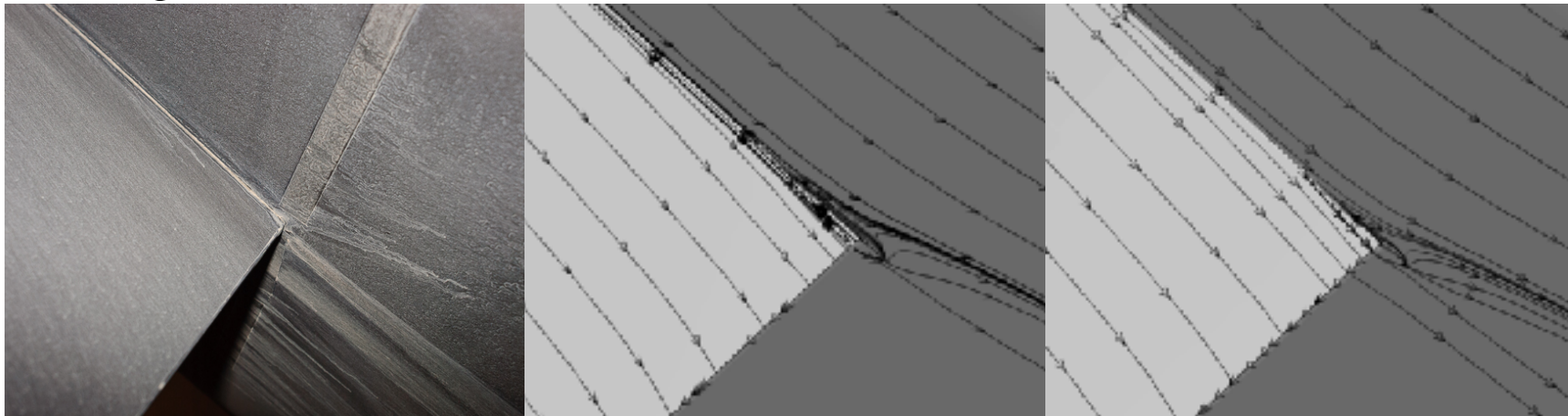
Experiment

CFD WT



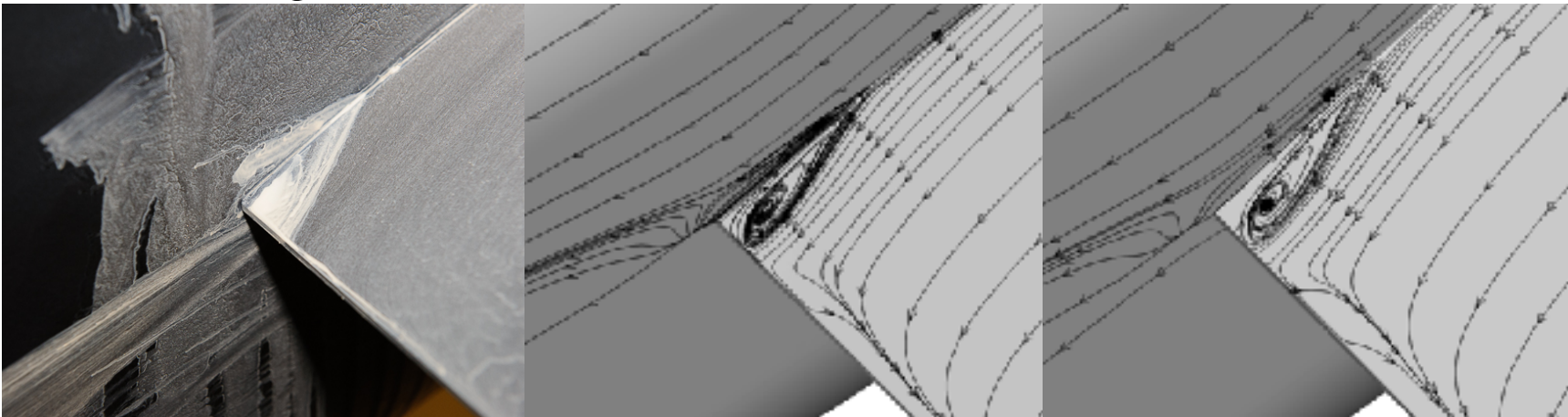
# Configuration 2: NACA 0015—NACA 0015mod, $\alpha=5.0^\circ$

Port Wing: NACA 0015 w/horn



\*Was run without horn

Starboard Wing: NACA 0015mod w/horn



Experiment

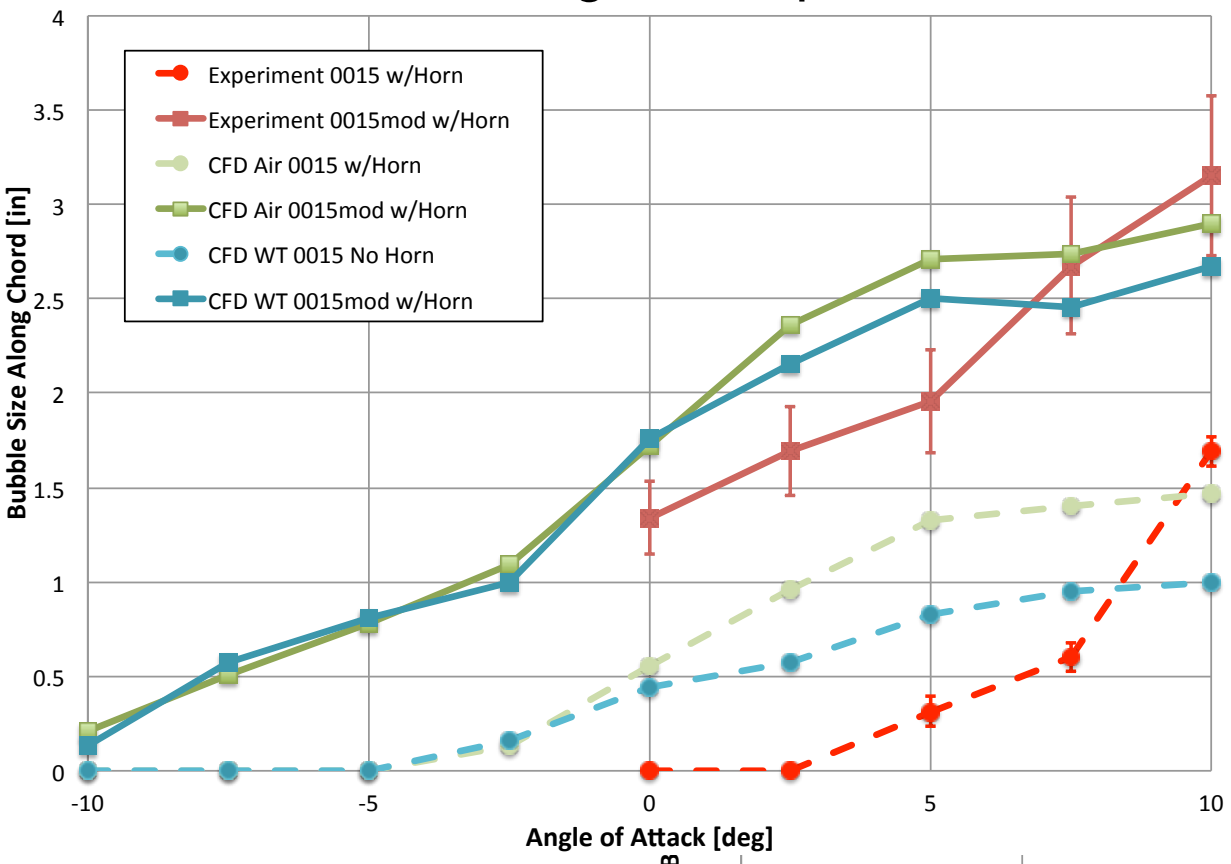
CFD Free Air

CFD WT

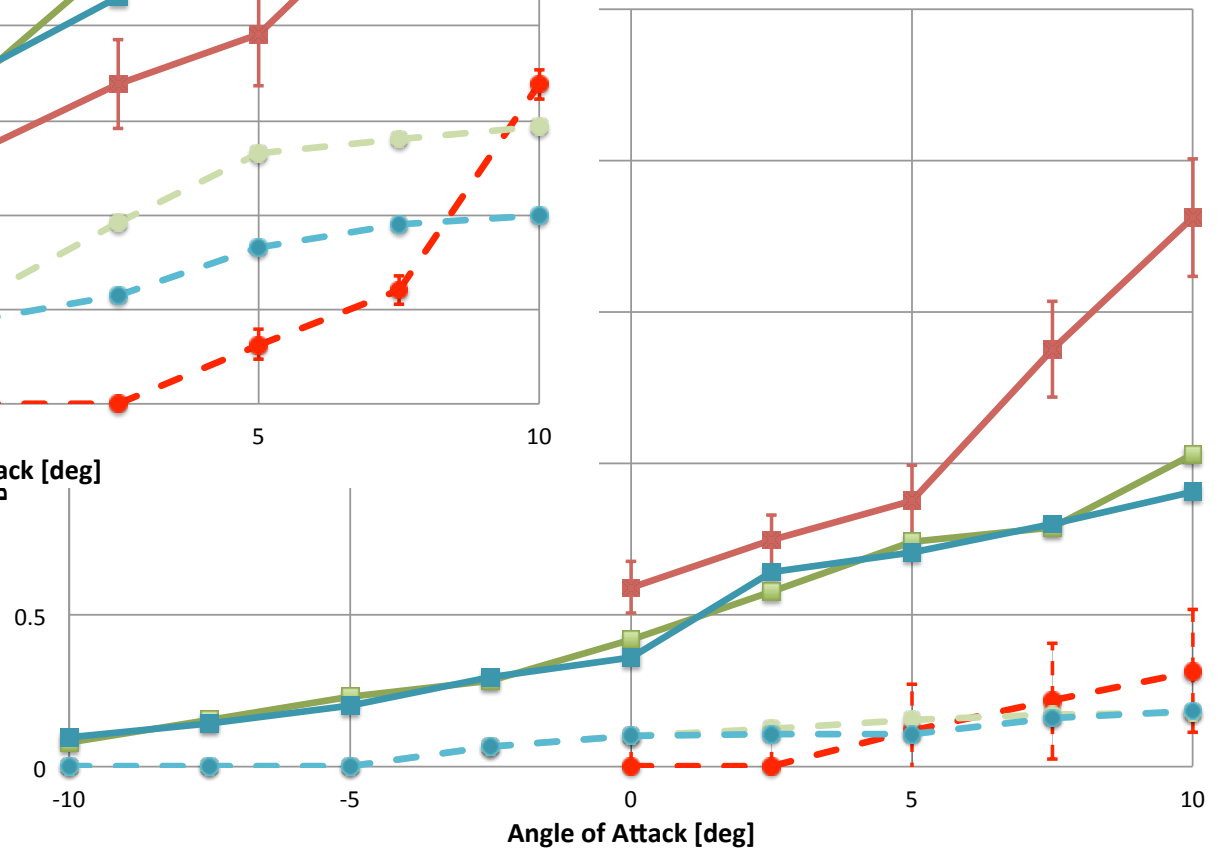
# Configuration 2: NACA0015—NACA0015mod



## Bubble Length Comparison



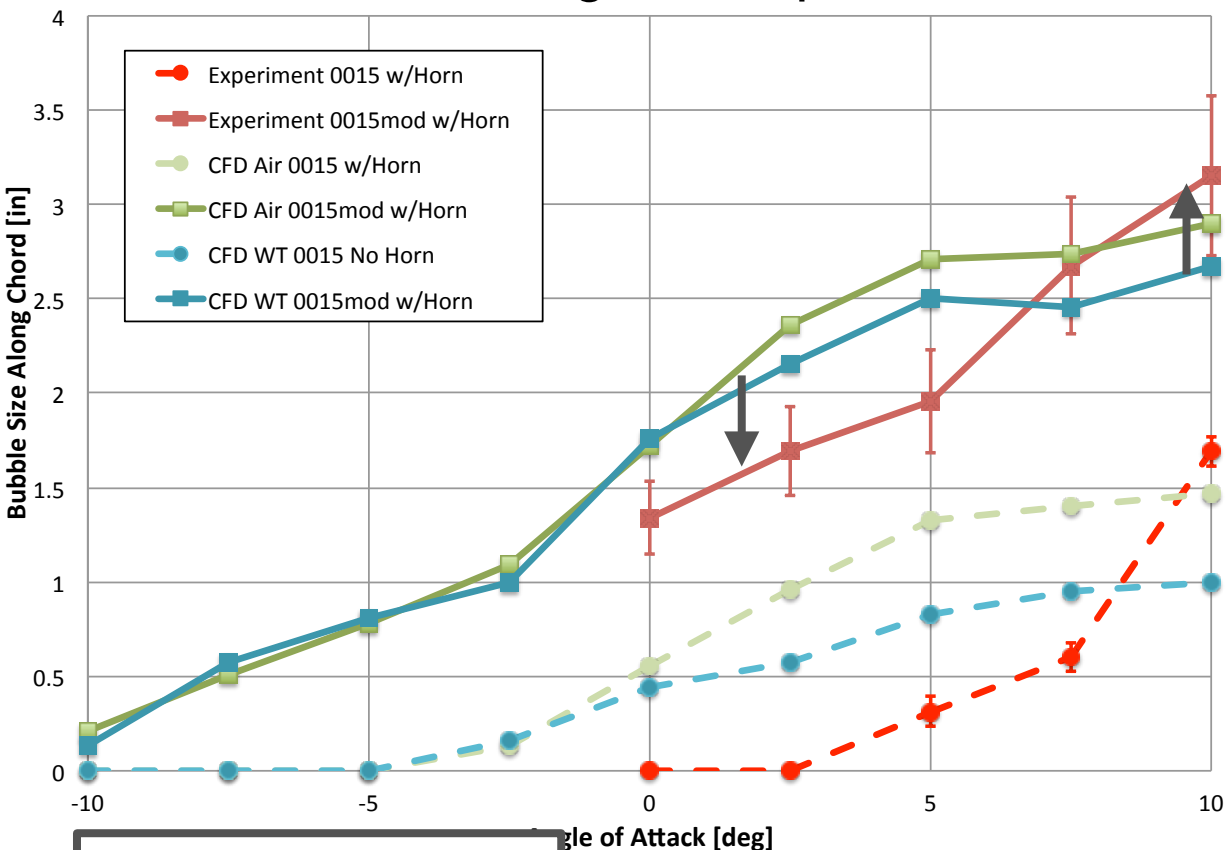
## Bubble Width Comparison



# Configuration 2: NACA0015—NACA0015mod

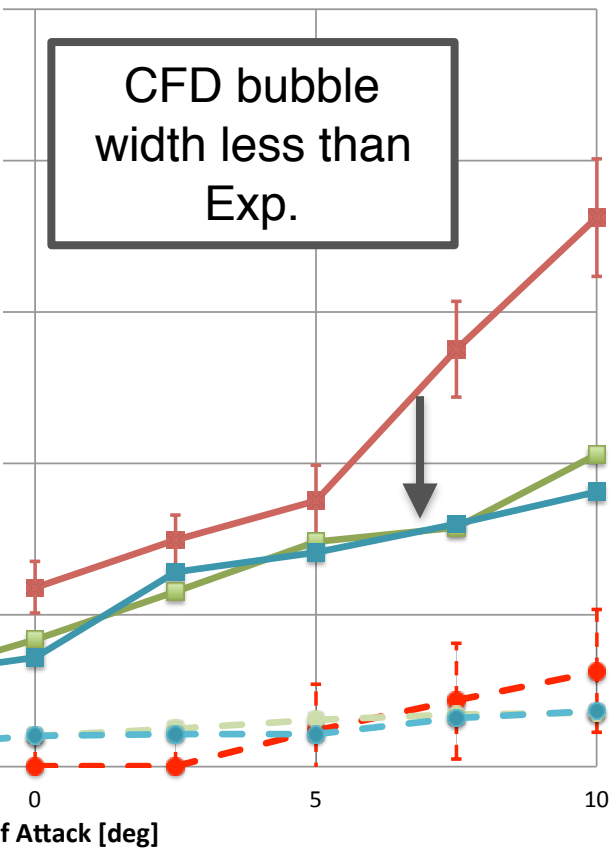


## Bubble Length Comparison



CFD Bubble Length slightly longer than Exp. at lower alpha, under predicts at high alpha

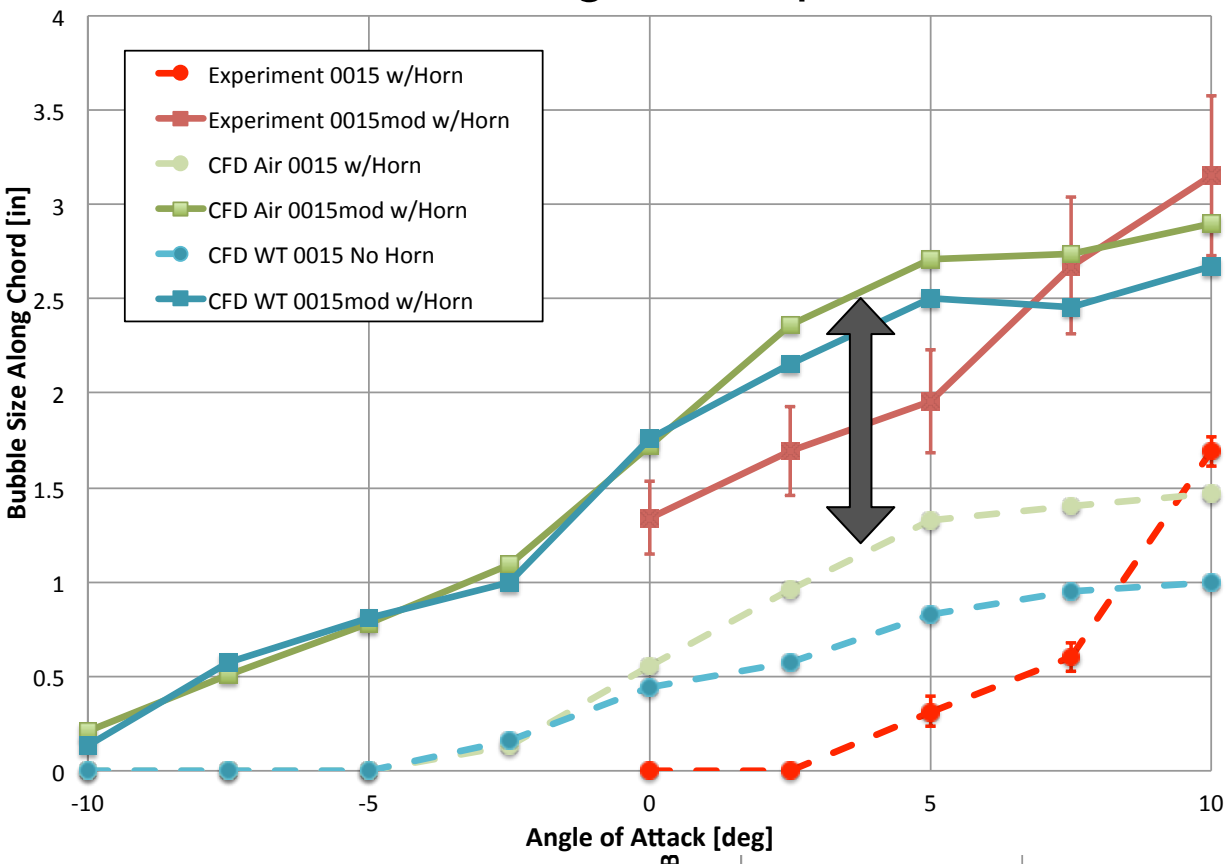
## Bubble Width Comparison



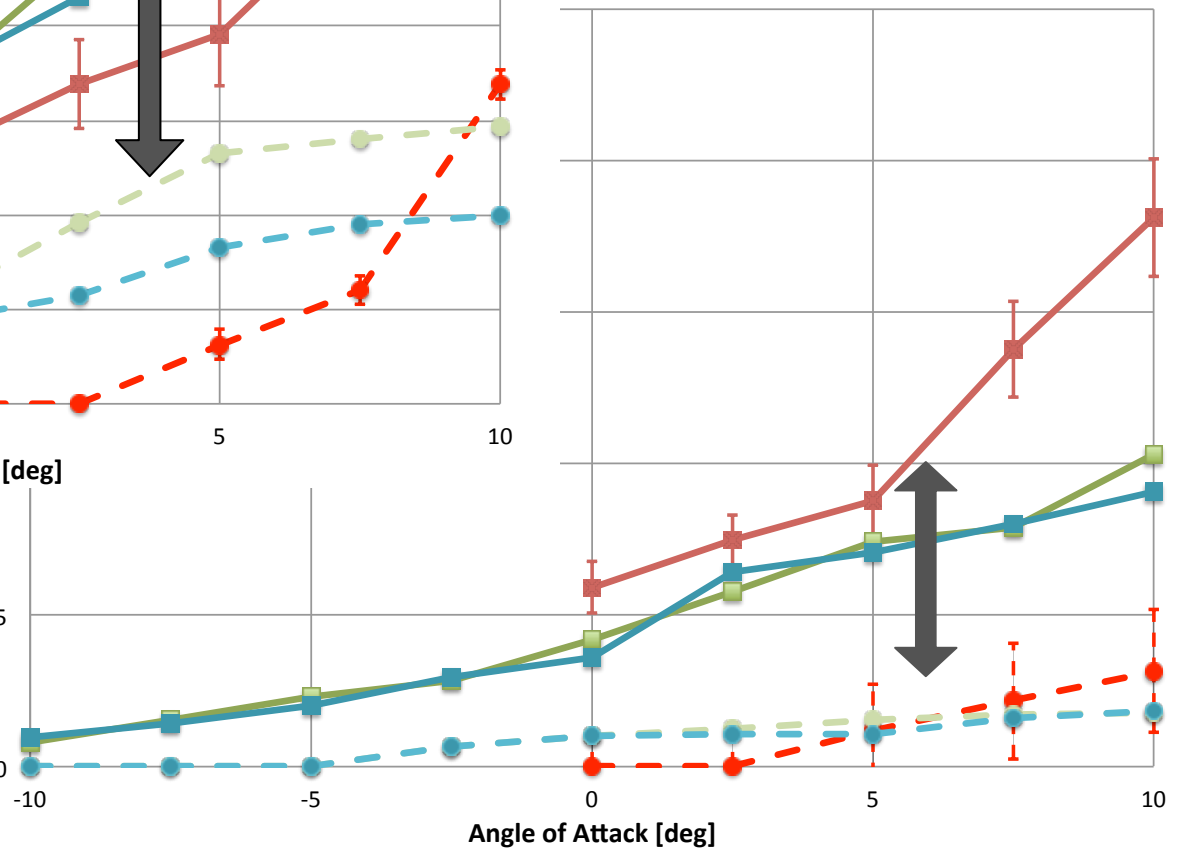
# Configuration 2: NACA0015—NACA0015mod



## Bubble Length Comparison



## Bubble Width Comparison

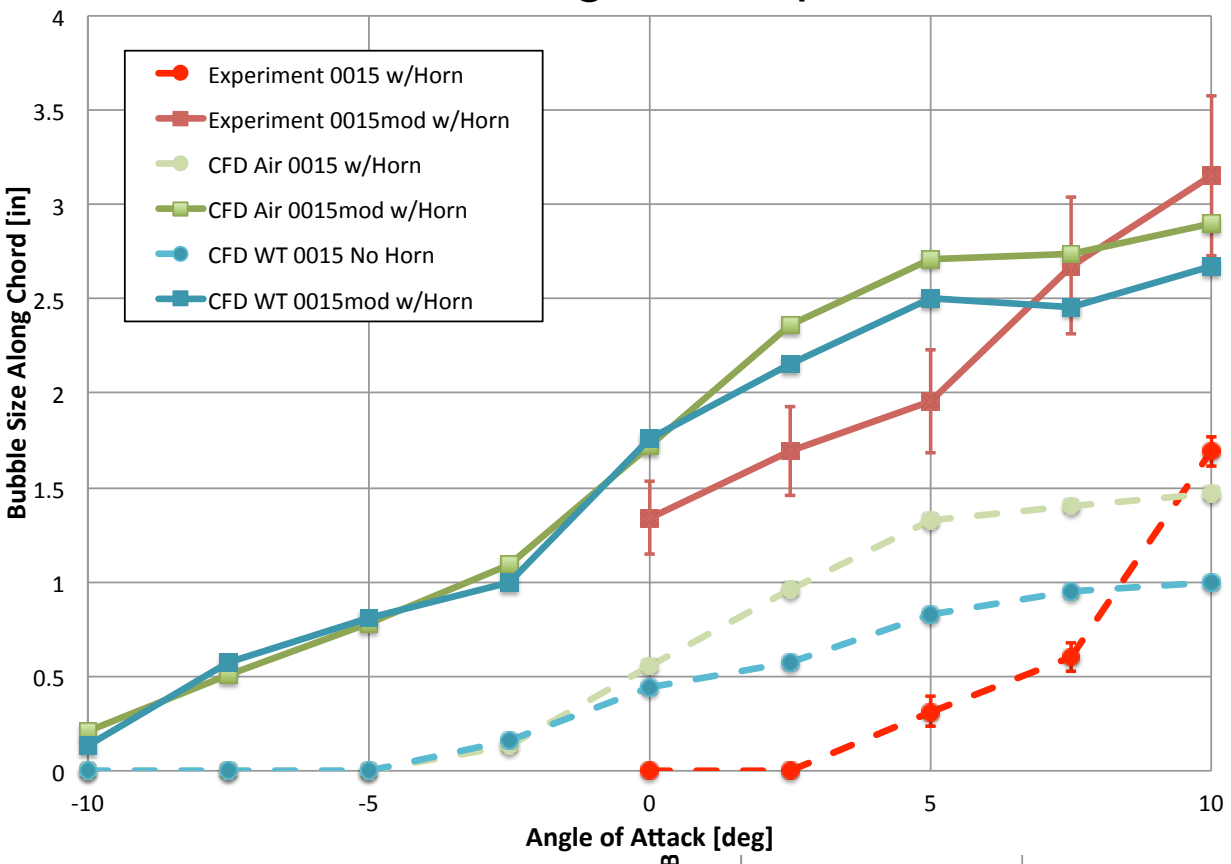


Increment between 0015 vs 0015mod wing consistent

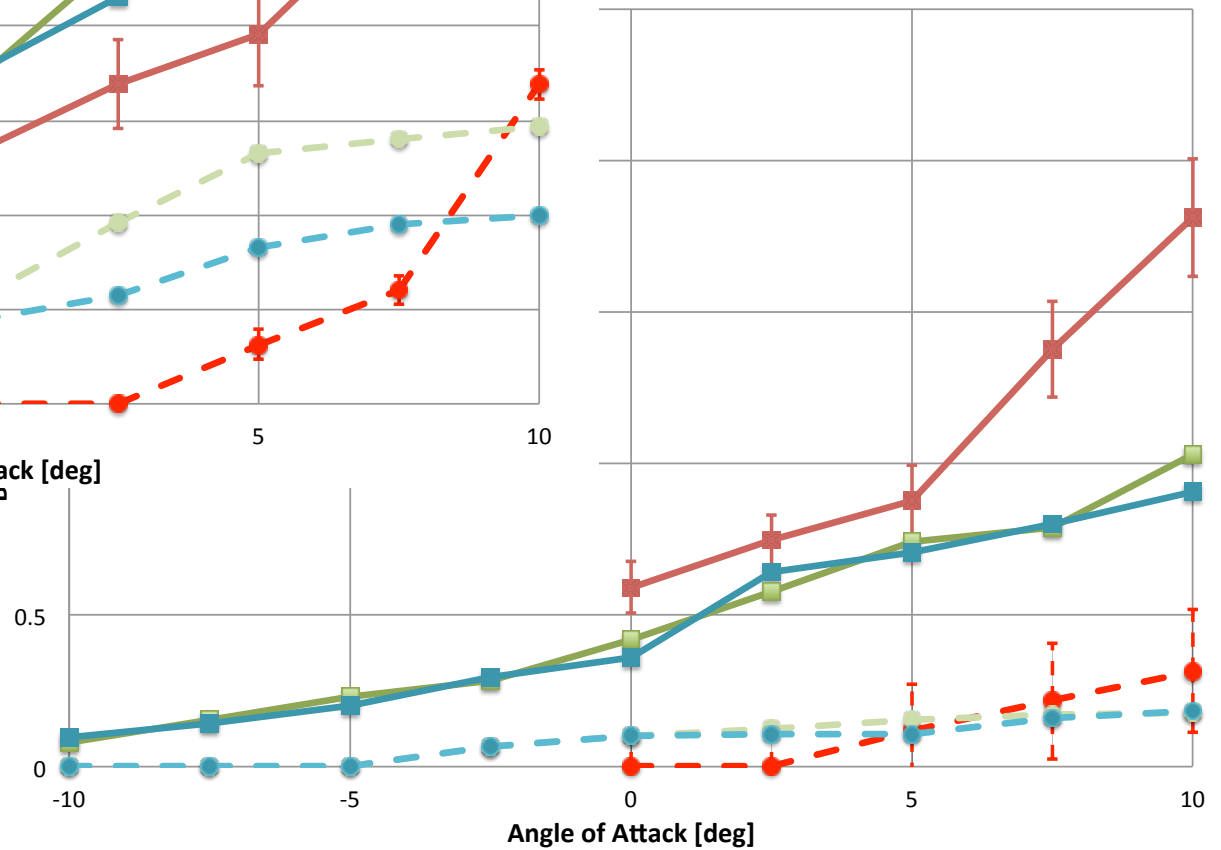
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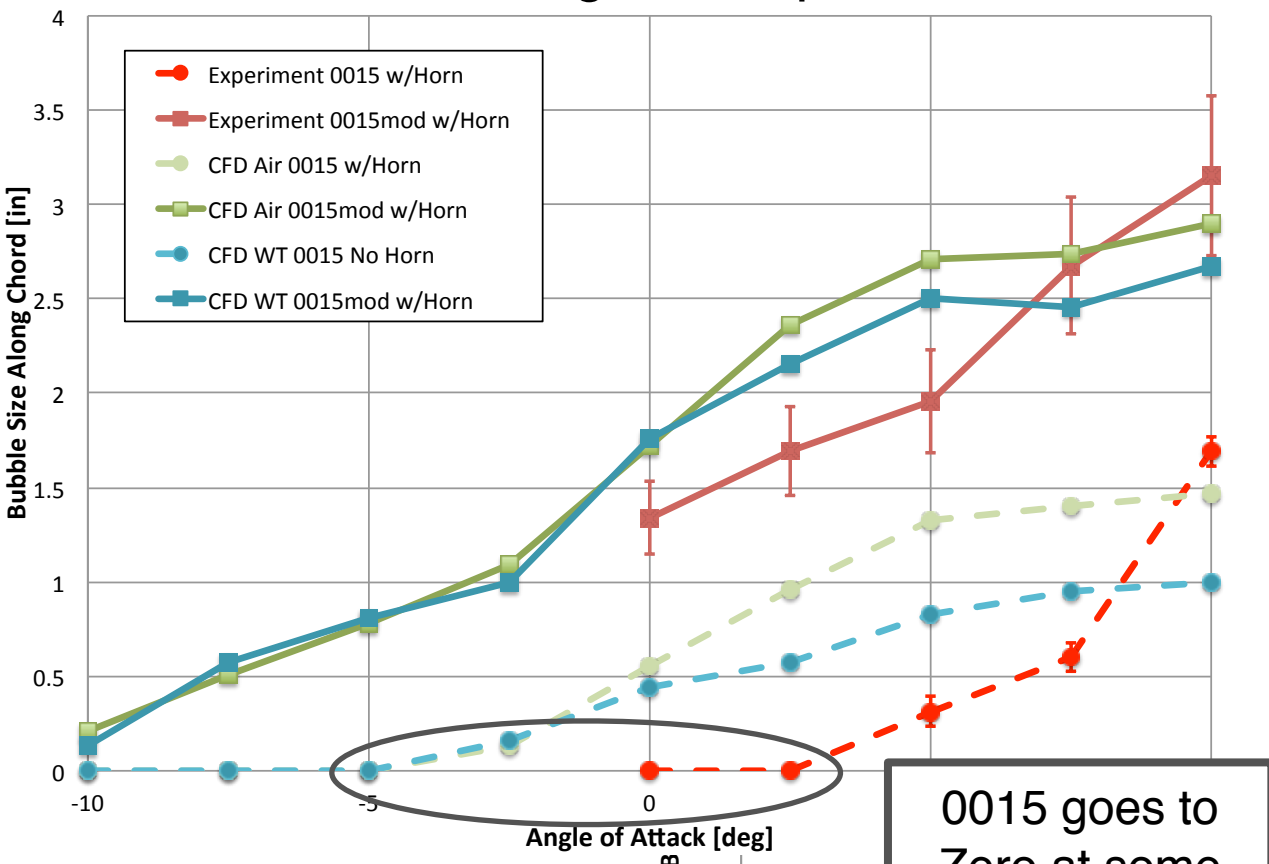
## Bubble Width Comparison



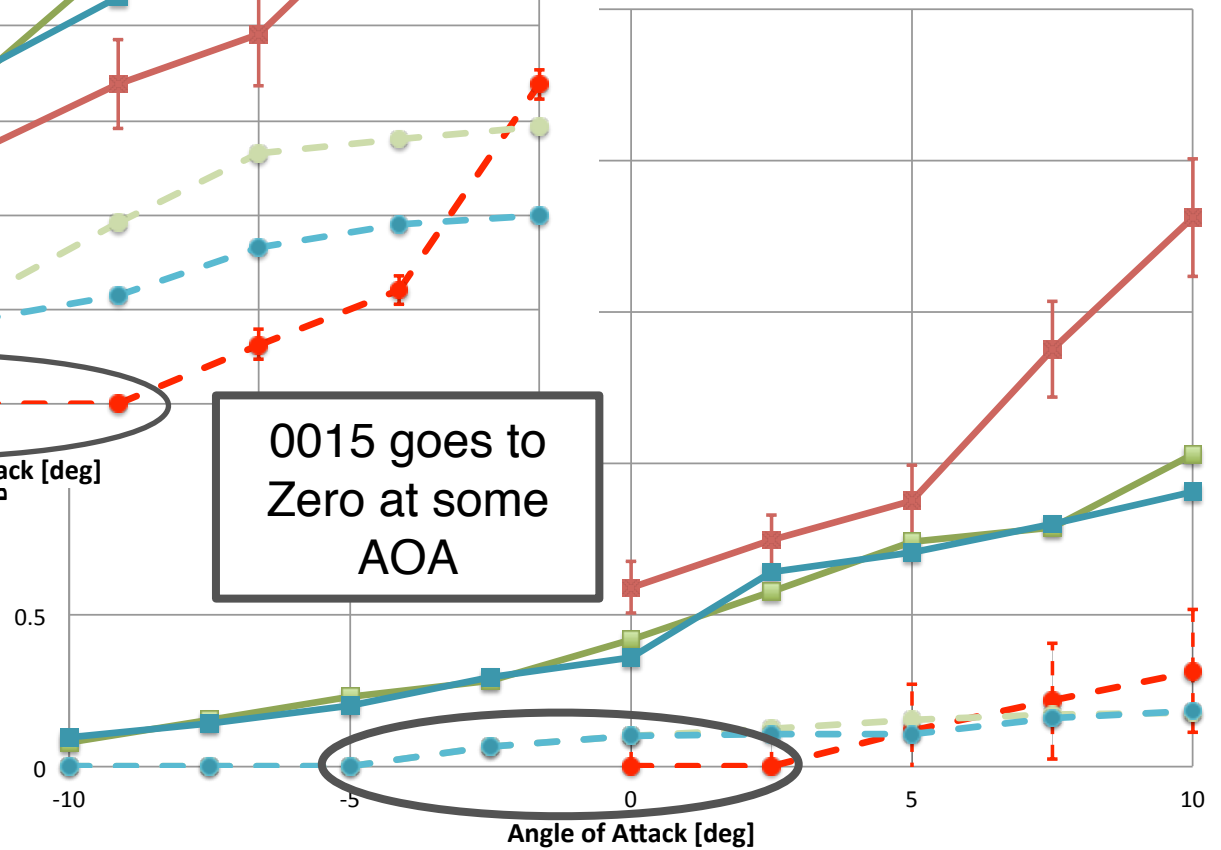
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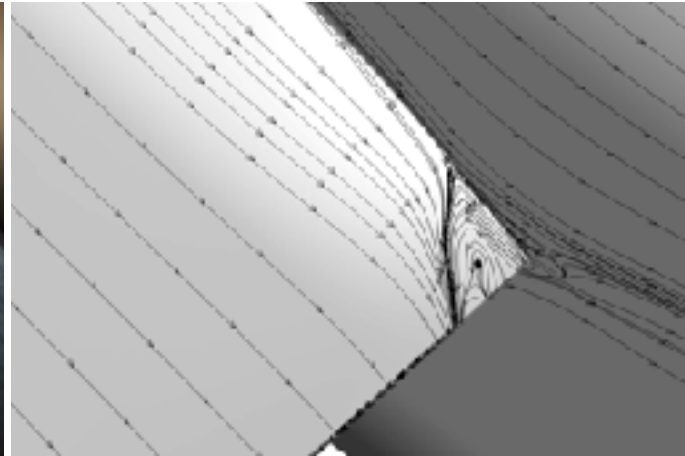
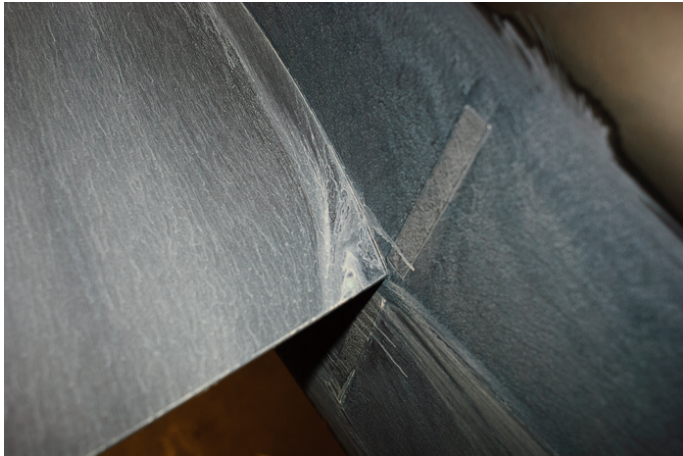
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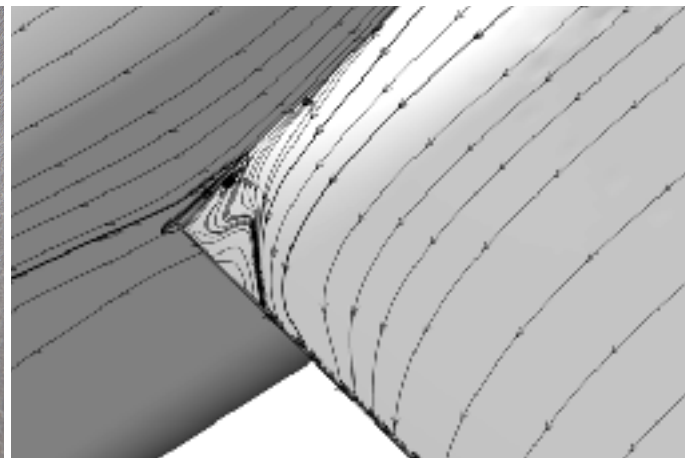
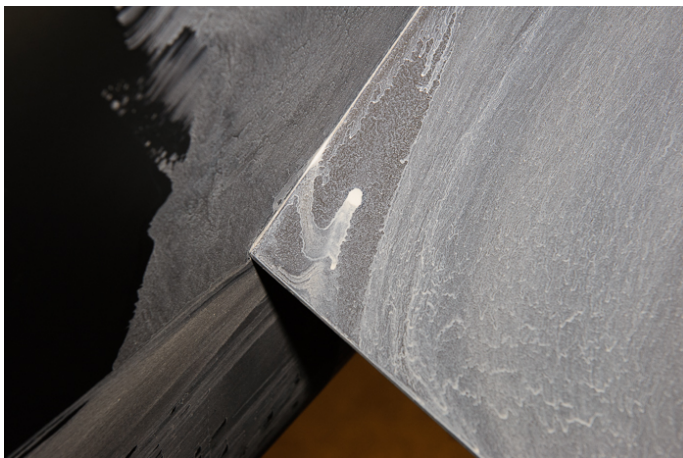
# Configuration 3: F6S12—COCA, $\alpha=5.0^\circ$



Port Wing: F6S12 w/horn



Starboard Wing: COCA w/horn



Experiment

CFD Free Air

# Wing Evaluations



- Trends between CFD and Experiment are very good
- F6 showed medium to large side of body separations
- NACA 0015 showed none to small separation
- NACA 0015mod showed small to medium separation
- COCA wing and F6S12 ruled out
- LE-horn indicates smaller LE horseshoe vortex

# Conclusions and Upcoming



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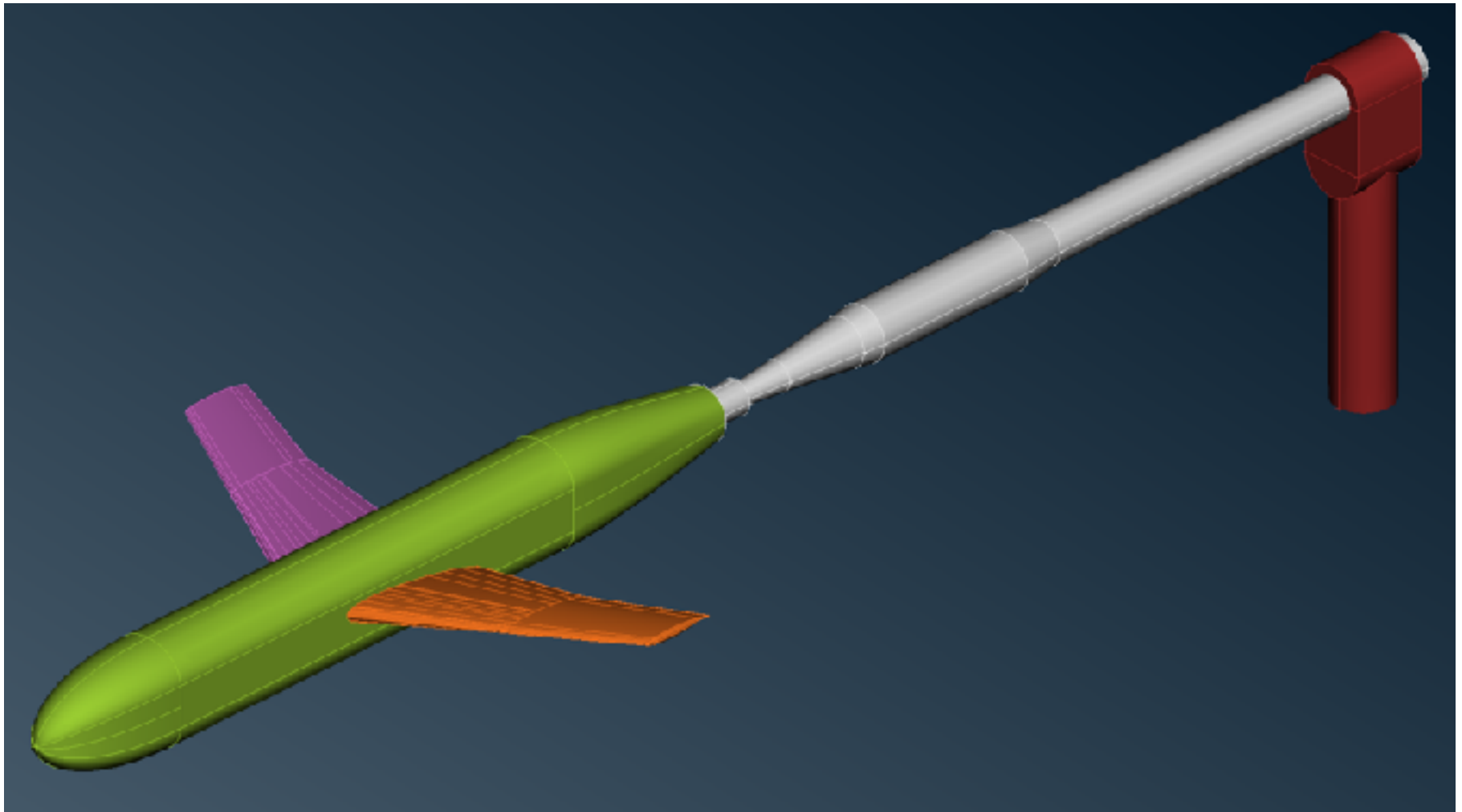
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- Tunnel entry 2: March 2018



# Upcoming CFD



Mock up of the JFM 8% model with roll sting and mast

# Upcoming CFD



- Run with Overflow & Fun3D
- Incremental buildup
  - Free air: JFM, JFM + Sting, JFM + Sting + Mast
  - 14x22 WT: JFM, JFM + Sting, JFM + Sting + Mast



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Side View Test Section

# Acknowledgements



## NASA's Transformational Tools and Technologies (T<sup>3</sup>) Project

Chris Rumsey and the Juncture Flow committee:

**NASA Langley:** P. Balakumar, Mark Cagle, Dick Campbell, Jan-Renee Carlson, Andy Davenport, Kevin Distill, Judy Hannon, Luther Jenkins, Bil Kleb, Mujeeb Malik, Cathy McGinley, Joe Morrison, Frank Quinto, Don Smith, Sandy Webb

**NASA Ames:** James Bell, Nettie Roozeboom, Laura Simurda, Greg Zilliac

**Boeing:** Mike Beyer, Neal Harrison, Peter Hartwich, Philippe Spalart, Tony Sclafani, John Vassberg

**AUR:** Gwibo Byun and Roger Simpson

**Virginia Tech:** Aurelien Borgoltz and Todd Lowe

**University of Kentucky:** Jim Coder

Bill Oberkampf